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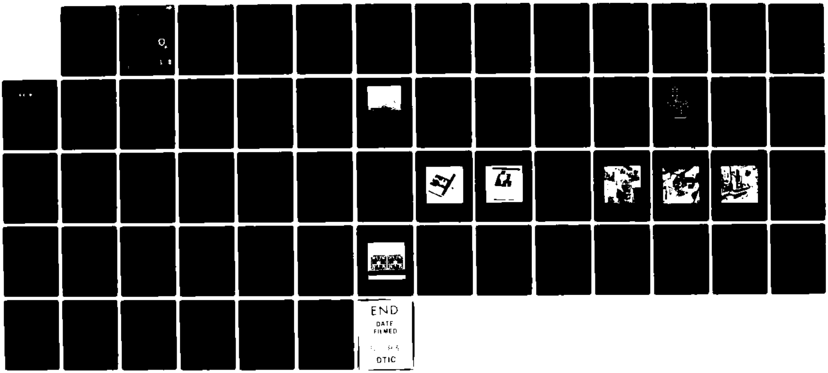

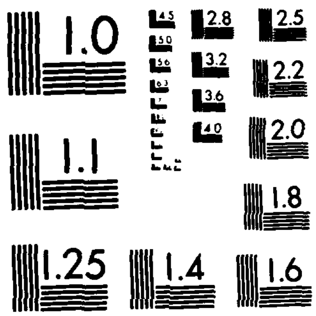

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Dual-Channel Fuel Control Program
Phase III

by
Mike Achmad

Prepared by
GARRETT PNEUMATIC SYSTEMS DIVISION
of The Garrett Corporation
111 South 34th Street
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Under Contract
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U.S. Army Electronics Research
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This report presents the results of a program conducted by Garrett to investigate a fluidic speed governor based on a laminar speed sensor for a dual-channel fuel control. The program provides a control system with requirements that are deemed necessary to provide a military gas turbine-powered vehicle with battlefield survivability and minimal restriction on the capability of completing the vehicle mission.

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20 Abstract (continued)

The study showed that the laminar speed sensor can be used for closed-loop speed control. It has the advantages of simplicity and a decreased number of components as compared to other approaches, yet it shows a higher signal-to-noise ratio than presently used devices, provides directional sensing, and has an efficient mechanical-pneumatic interface.

FOREWORD

This is the final report of a program conducted by Garrett Pneumatic Systems Division (GPSD) of The Garrett Corporation. The purpose of this program was to develop a dual-channel electrical and fluidic fuel control for application on typical military automotive gas turbine engines. This report covers the third phase of the program which was devoted to the development of a fluidic speed governor based on a laminar speed sensor.

The program was authorized by the Naval Air Systems Command under Contract N00019-78-G-0288 and was monitored by Mr. John Goto of Harry Diamond Laboratories of the Department of the Army. The program was conducted from May 1980, to April 1982.

Publication of this report does not constitute approval by any member of the Department of Defense of the findings or conclusions contained herein.

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1. INTRODUCTION

This is the final report of Phase III of a program conducted by Garrett Pneumatic Systems Division to develop a fluidic speed governor. The governor is based on a laminar speed sensor used on a dual-channel fuel control. The control is intended for use on a military gas turbine engine such as the ITI-GT601. The primary objective of the program was to obtain a control system with two complete and parallel modes of control represented by dissimilar technologies. To this end, the primary controller is electronic while the secondary controller is fluidic.

The task to be performed in this phase of the program was to develop and test a fluidic speed governor based on a laminar speed sensor. The governor was installed and tested on an industrial air/gas turbine starter, Garrett Model ATS500-1.

1.1 Background. The dual-channel fuel control concept is seen as a means of increasing the survivability of combat vehicles in battle conditions. Presently, controls on some military gas turbines provide only a marginal "limp-home" backup mode in the event that the primary controller (electronic) fails and the capability for restart is also lost.

In Phase I of this program (the results of which were presented in Report HDL-CR-78-186-1), it was determined that the dual-channel fuel control concept was feasible. The ITI-GT601 gas turbine was used as a model. Beyond the conventional fuel control parameters used with gas turbine engines, the GT601 engine has a variable turbine nozzle (VTN) system and a recuperator (stationary) heat exchanger which increases the required control parameters for this engine.

In Phase II of this program (the results of which were presented in Report HDL-CR-81-288-1), it was determined that a parallel dissimilar technology backup control was the desirable approach. Fluidics was the ideal technology to perform this function due to its low cost, reliability, immunity to radiation, and ability to perform computation and logic commensurate with the requirements of achieving mission completion. This can be accomplished with no degradation in the battlefield survivability of the vehicle.

1.2 Summary. Phase III of the Dual-Channel Fuel Control Development Program addressed the fluidic speed governor based on a laminar speed sensor.

This program report is divided into two major sections that discuss the two aspects of the program. Section 2 contains a discussion on the progress of the dual-channel fuel control designed for the ITI-GT601 engine. Section 3 addresses the development work for the fluidic speed governor for demonstration on the Starter Model ATS500-1. Sections 4 and 5, respectively, present the conclusions and recommendations based on the results of the development program.

Appendices included in this report present detailed information on some of the fabricated hardware.

2. DUAL-CHANNEL FUEL CONTROL ON GAS TURBINE ENGINE MODEL ITI-GT601

2.1 Background. To date, gas turbine engines have been used primarily to power aircraft as their main means of propulsion and to provide electrical, hydraulic, and pneumatic power for stationary applications such as off-shore oil drilling rigs, hospitals, computer centers, etc. Today, with the advent of increased difficulty in obtaining low-cost, high-quality oil suitable for gasoline engines, there is renewed interest in the gas turbine engine for on- and off-road vehicles.

One of this new generation of gas turbines is the ITI Model GT601 engine which is being developed by The Garrett Corporation for use in trucks and tracked vehicles. To optimize its performance and achieve or exceed the fuel efficiency of diesel engines, these gas turbines rely on complex electronic fuel controls. Questions have been raised by the military as to the survivability of complex electronics under battlefield conditions. Therefore, backup controls must be provided with a high level of complexity while using an alternate technology.

Fluidics can provide this computational capability and the level of survivability required. Therefore, the dual-channel or dual-technology fuel control concept was generated to fulfill this need.

2.2 Program Outline. During initial feasibility study of the dual-channel fuel control, major blocks of the unit were identified and the program was divided into seven phases, each containing a program to develop certain major blocks of the unit. The major blocks of the dual-channel fuel control are shown schematically in figure 1 and a summary of each phase of the program is outlined in table I.

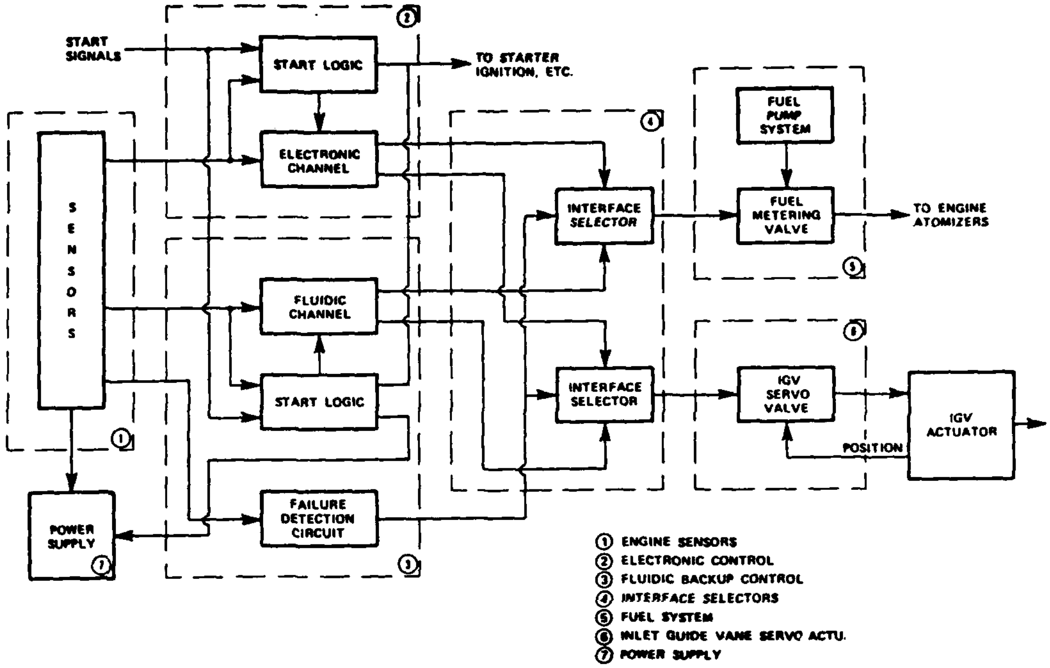


Figure 1. Block diagram of the dual channel fue trol.

TABLE I. PROGRAM OUTLINE FOR THE DUAL-CHANNEL FUEL CONTROL

Program Phase	Description
I	Determine the practicality of the concept, conduct a feasibility study, and provide a recommended approach.
II	Develop hardware for the failure detection circuit.
III	Design and fabrication of the control components and development of the start logic circuit.
IV	Design, fabrication, and test of the fluidic channel of the fuel control
V	Design, fabrication, and test of the fuel metering valve and inlet guide vane actuator compatible with both the fluidic and the electronic controls.
VI	Conduct engine test and bench test of the fluidic fuel control.
VII	Conduct bench and engine test for the combined electronics and fluidic channels.

2.3 Phase III Work Statement. The tasks to be performed in Phase III of the dual-channel fuel control program were divided into three main categories as follows:

1. Determine the proximity of all sensors and any special circumstances with respect to the fluidic fuel control and engine interface.

2. Develop and fabricate all sensors required for the interface of the fluidic fuel control and the engine. The sensors consist of the following:

   a. Speed sensors for

      - gas generator shaft
      - power turbine shaft

   b. Temperature sensors

      - T_4 turbine inlet temperature
      - $T_{3.5}$ compressor outlet temperature
      - T_2 inlet/ambient temperature
      - T_6 recuperator temperature

   c. Pressure sensor

      - $P_{3.5}$ compressor output pressure

3. Develop start sequence logic circuit compatible with sensor outputs.

2.4 Gas Turbine Engine Model ITI-GT601. Gas Turbine Engine Model ITI-GT601 was originally designed for application in commercial trucks as a replacement for the more traditional diesel and regular combustion engines. Presently, research is being conducted relative to use of the engine in military vehicles such as armored personnel carriers, tanks, and even tank carriers. This rather revolutionary application was the result of the tradeoffs inherited by the gas turbine engine. The gas turbine-powered vehicles have been claimed to have faster and smoother acceleration, smaller space requirements, quieter operation, and increased drivability and economy.

The basic components of Model ITI-GT601 engine are depicted schematically in figure 2. As shown, the engine comprises a two-stage compressor, a single turbine, a two-stage power turbine, a combustor, and a heat exchanger. The engine operates on an open cycle (Brayton cycle) where the heat exchanger is included to provide increased efficiency.

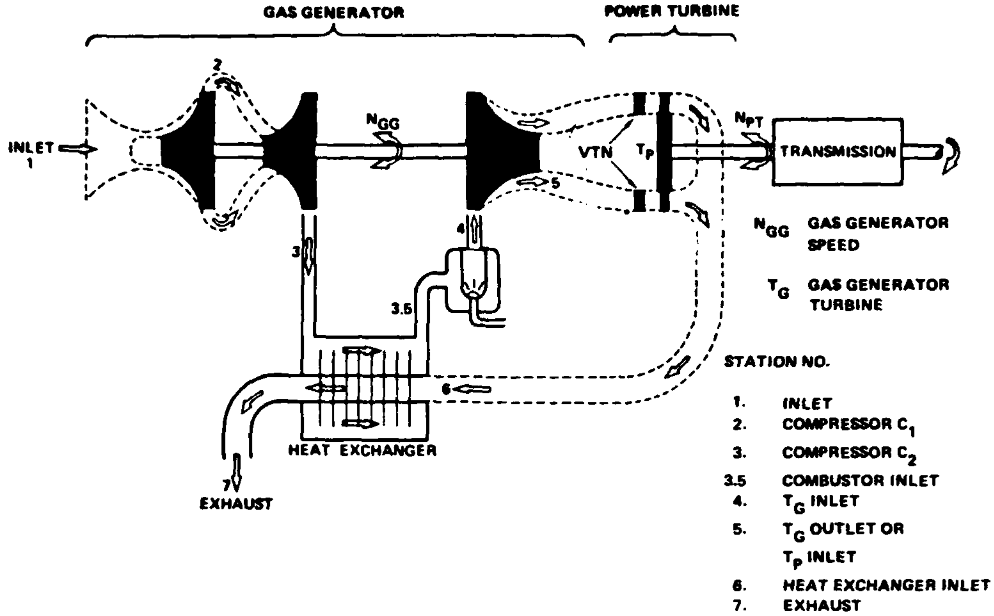


Figure 2. Schematic of Model ITI-GT601 gas turbine engine with station numbers designation.

2.5 Present Fuel Control on Model ITI-GT601 Engine. This fuel control system depends upon hydromechanical hardware to meter the fuel and establish power turbine vane angles necessary for rated power and to permit manual transmission shifting. Electronic controls and electrical speed, pressure, and temperature sensors optimize fuel economy, provide flat rate power, maintain engine temperature limits, and permit engine starting.

The driver input for operation of the engine is similar to that of a diesel power plant. A key switch supplies power to the electronic control and arms the momentary start switch which activates the autostart sequence. This automatically accelerates the engine to idle speed or aborts the start and drains fuel from the engine on failure to ignite. From idle to rated power, gas generator speed and the vane angle for acceleration and deceleration are controlled by the foot throttle. When the key switch is turned off, fuel and electrical power to the engine are shut off.

Major control system components are shown in a schematic in figure 3. The fuel management system, consisting of a fuel pump and governor, scheduling valve, and T_2 compensation valve,

meters fuel to the engine. The variable turbine nozzle (VTN) positioning system consists of an actuator which positions the vanes in response to electronic and hydraulic signals. The electronic control processes signals from the engine, actuator, and driver, and, in response, sends signals to the actuator and pump and governor to position the VTN or reduce fuel flow. The hydraulic speed sensor and T_4 sensor send signals to the actuator and electronic control, respectively.

Once started, the engine can be accelerated, decelerated, and the clutch disengaged if necessary, without electrical power, assuming that power to the three-way fuel shutoff solenoid is uninterrupted.

2.6 Dual-Channel Fuel Control on Model ITI-GT601 Engine. Several different arrangements for the dual-channel fuel control can be realized. In general, the dual-channel fuel control consists of the primary and the secondary fuel control, with each separate control capable of independently controlling the engine. Variation may be obtained by having primary and secondary sensors.

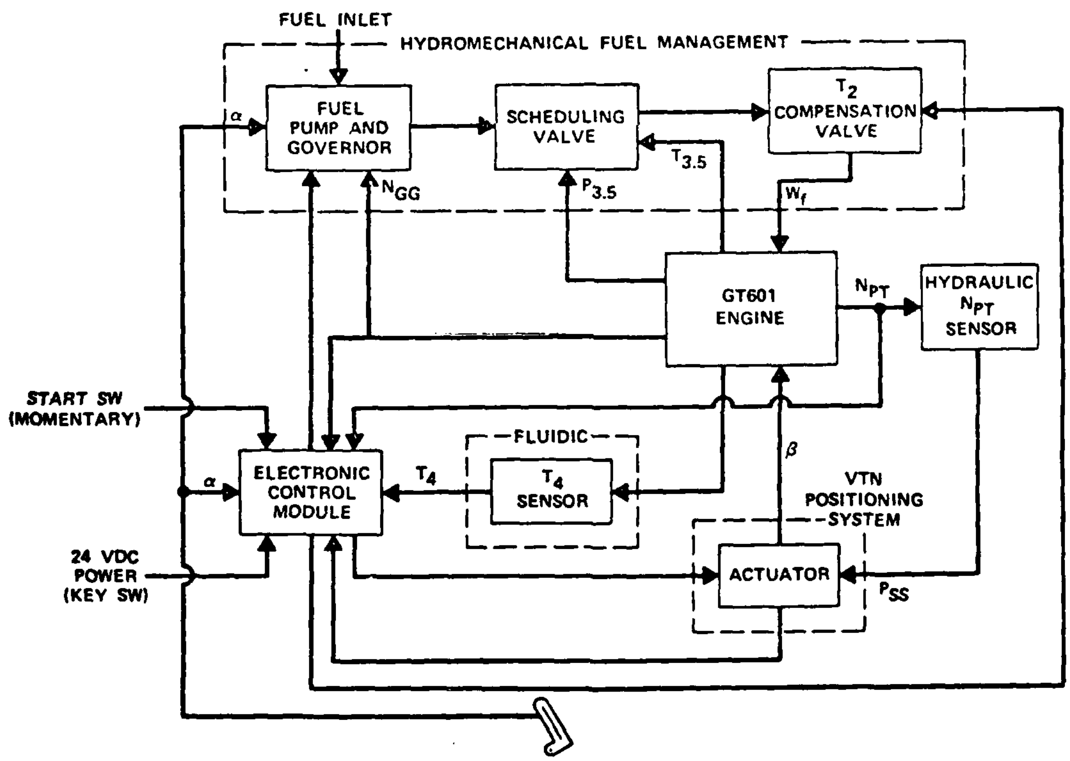


Figure 3. ITI-GT601 electromechanical fuel control system schematic.

The recommended approach for the dual-channel fuel control is basically shown in the preceding figure 1. In this configuration, some of the sensors will provide input to both the electronic and the fluidic channel. An example is the T_4 sensor which will be discussed in a later section.

Each fuel control element in the dual-channel fuel control will be developed to start and operate the engine independently and safely. The fluidic channel may not be capable of running the engine with the same fuel efficiency as the electronics since it will require a more complex fuel control in order to meet the extensive computation requirements. However, both the electronic fuel control and the fluidic fuel control will provide similar safe full power engine operation and identical performance on the battlefield.

2.7 Program Development.

2.7.1 Preliminary Interface. The addition of the fluidic fuel control to the present ITI-GT601 gas turbine engine depends on the flexibility of the fluidic fuel control. Considering the cumbersome modification to the engine and the extra cost, a simplified fuel control implementation is necessary. Thus, from an initial look at the ITI-GT601 engine, some preliminary approaches for the fluidic fuel control interface were considered. These are summarized as follows:

- To minimize pneumatic lines and to ease gas generator speed sensing, the fluidic circuit is to be located at the present fuel pump interface.
- A separate compressor is required for the start cycle when the fluidic channel is selected but the gas generator bleedoff can be used once the engine is running. (This parallels the fuel nozzle compressor requirement, thus requiring a small increase in the existing compressor size.)
- Electrical power is required to start the engine even when the fluidic channel is selected.

Some of these preliminary approaches are considered important in order to define a clear objective in the overall program.

2.7.2 Sensor Development. Three basic sensor requirements were established for the GT601 dual-channel fuel control: speed, temperature, and pressure sensors. These sensor requirements are summarized in table II. The following paragraphs present descriptions of the sensor requirements and indicate the approaches to be pursued.

TABLE II. GT601 SENSOR REQUIREMENTS FOR THE DUAL-CHANNEL FUEL CONTROL

Parameter	Location in GT601	Input/range	Fluidic circuit used	Possible secondary circuits	Function and description
N_{GG}	On existing fuel pump interface	Zero to 4785 rpm	Laminar amplifier/ chopper	Gain block frequency-to-analog and gain block	Logical: N_{GG} = 12 percent, 45 percent, 50 percent Proportional: N_{GG} = 50 percent to 100 percent
N_{PT}	Existing N_{PT} sensor	Hydraulic pressure	Pin amplifier	Gain block	Overspeed warning: N_{PT} = 105 percent
T_6	Recuperator	70 F to 1300 F	Oscillator	Frequency-to-analog and gain block	Overtemperature
T_4	Existing turbine	1000 F to 2000 F	Oscillator	Frequency-to-analog and gain block	Logical: overtemperature proportional: for fuel metering
$T_{3.5}$	Existing temperature sensor	Zero to 990 F	Oscillator	Frequency-to-analog and gain block	Acceleration
T_2	Inlet duct	Minus 40 F to 103 F	Capillary and orifices bridge	Gain block	Fuel compensation
$P_{3.5}$	Compressor outlet	Zero to 125 psig	Vortex orifice	None	Fuel compensation

Speed sensors.--Two speed sensors are required for the dual-channel fuel control. The first is used to sense the speed of the gas generator while the second is for sensing the speed of the power turbine shaft.

The sensor for the gas generator shaft speed can be mounted on the present fuel pump shaft which has gone through a speed reduction of 7.85 (100 percent of N_{gg} = 37,540 rpm). The speed range of zero to 5000 rpm is quite suitable for the range of the fluidic speed sensors. As shown in table II, the N_{GG} must produce both logical and proportional outputs. The logical output has three set points (12 percent, 45 percent, and 50 percent N_{GG}). The N_{GG} range from 50 to 100 percent must be proportional. Fluidically, two viable types of speed sensors can be applied to the N_{GG} sensors. These sensors are laminar speed sensors and chopper/digital speed sensors. The latter has been used in a number of applications (gun sensors and thrust reversers) and has shown field reliability and survivability, mainly due to its simple operation and construction. The laminar speed sensor is recently developed and has been shown to have an improved signal-to-noise ratio. The sensor was developed and tested on the ATS500-1 (see description in section 3).

The present hydromechanical speed sensor for the power turbine shaft can be modified by adding a pin amplifier arrangement to give pneumatic output. The requirement for this speed sensor is relatively simple, since it is for overspeed operation only.

The other option is to sense the power turbine speed at the lay shaft which has gone through a speed increase of 8.142 (N_{PT} 100 percent = 3000 rpm and N_{PT} idle = 750 rpm). Either of the two fluidic speed sensors can be used.

Pressure sensor.--The purpose for sensing the compressor output pressure ($P_{3.5}$) is to compensate the scheduling valve in the ITI-GT601 engine fuel metering section. The ranges of $P_{3.5}$ are typically from zero to 125 psia. To sense this high pressure as input into the fluidic computation circuit, fluidic vortex orifices can be used in series with either the fluidic amplifier or the rectifier. The circuit will reduce the input pressure to the operating pressure level of the fluidic circuit. A sample of the vortex orifices for the pressure sensor is shown in figure 4.

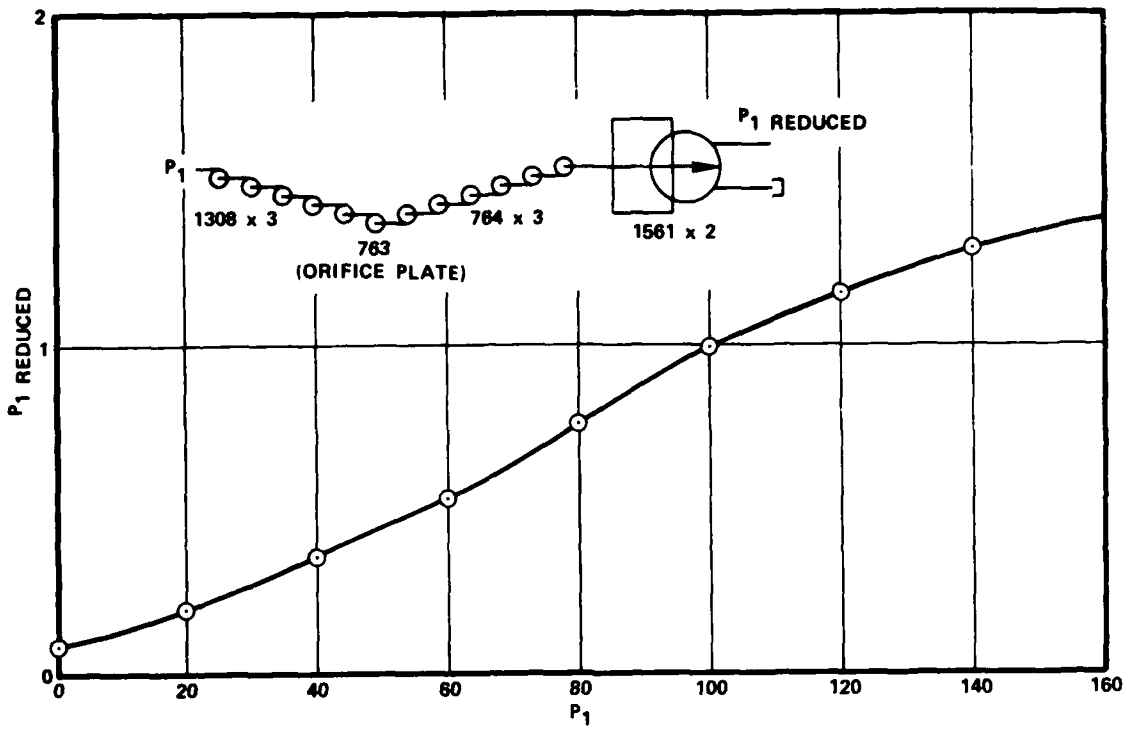


Figure 4. Vortex orifices for the pressure sensor sample.

Temperature sensors.--Of the four temperature sensors required for the ITI-GT601 engine dual-channel fuel control shown in table II, the T_4 sensor (turbine inlet temperature sensor) is the most critical because it has a relatively high operating temperature (ranging from 1000 F to 2050 F). The specification requirement for the T_4 sensor is tight since it must be able to measure a temperature variation of ±10 F at its nominal operating temperature of 1900 F.

The present electrohydromechanical fuel control utilizes the fluidic oscillator temperature sensor shown in figure 5 to sense turbine inlet temperature.

To minimize the change on the engine housing, the fluidic T_4 sensor can be modified to provide both pneumatic output for the fluidic channel and an electrical output for the electronic control module. The T_4 sensor with dual output is shown schematically in figure 6. The basic T_4 sensor comprises a coiled

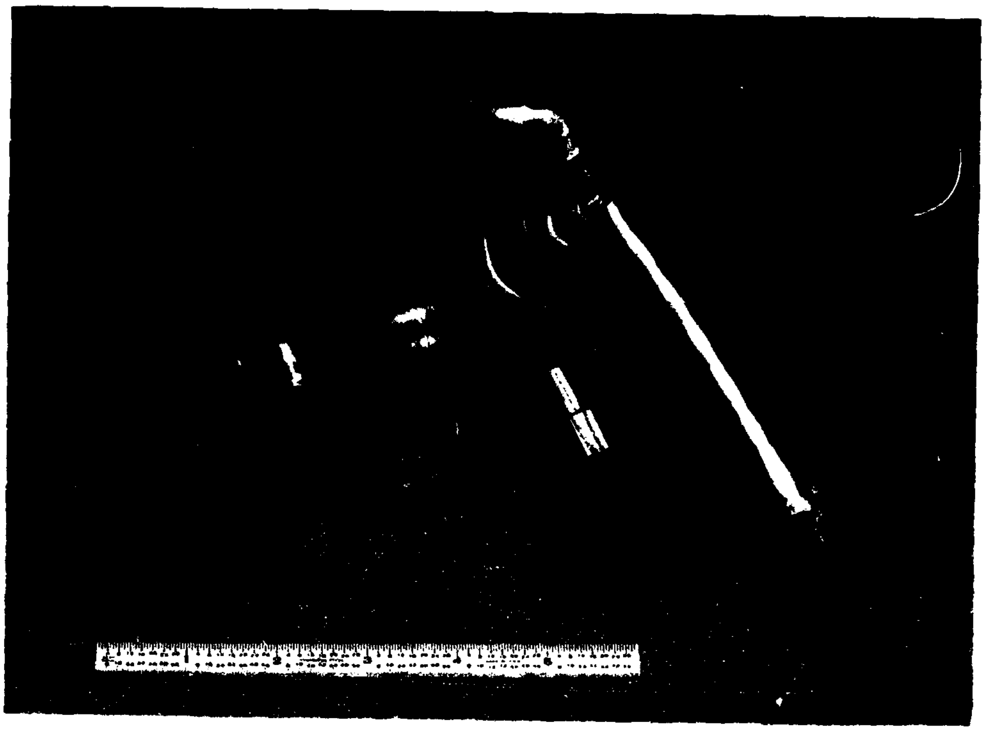


Figure 5. T_4-turbine inlet temperature sensor.

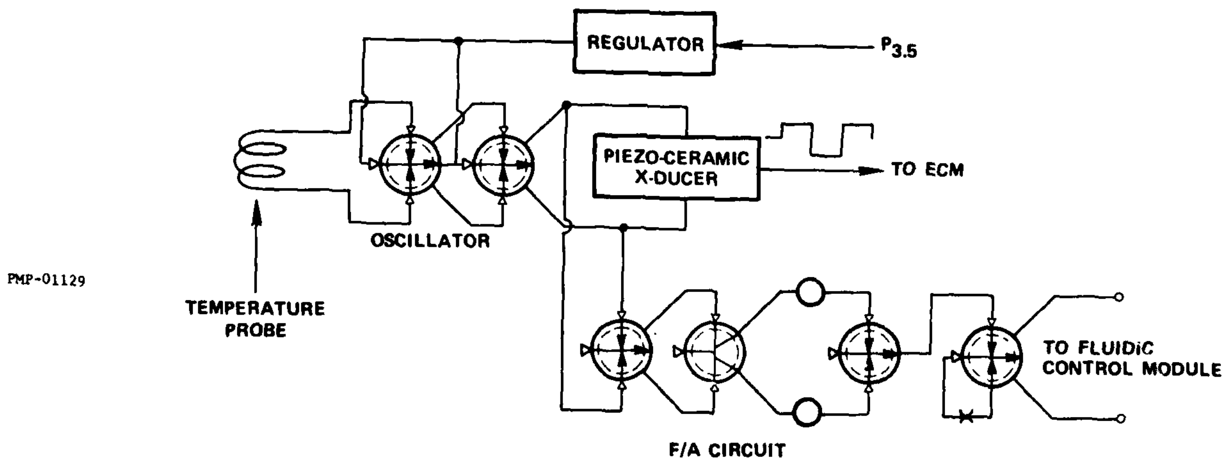


Figure 6. T_4-turbine inlet temperature sensor schematic with electrical and pneumatic output.

tube as the probe, a fluidic oscillator, a regulator (which regulates the supply pressure to the oscillator), and a piezoceramic transducer (which senses the oscillator output). As shown in figure 6, the only addition to the basic T_4 sensor is the frequency-to-analog (F/A) circuit and two ports which tap the oscillator output.

The other temperature sensor requirements (T_6, $T_{3.5}$, T_3, $T_{3,5}$) can be designed using a concept similar to that of the T_4 sensor. However, when lower temperature ranges exist, such as in the T_2 sensor, capillary and orifice bridge network can also be used.

2.8 Start Sequence Logic Circuit. The purpose of the start sequence logic circuit is to schedule the starter and fuel meter during the starting cycle of the engine. In the dual-channel fuel control, the fluidic start sequence logic must perform in the same way as the electronic start logic circuit shown in figure 7.

The inputs to this circuit are the start signal, N_{GG} 10-14 percent, N_{GG} 42-45 percent, and T_4 sensor output. The outputs are signals to the starter motor, ignition driver, and fuel solenoid valve. The 23-second delay time is activated when lightoff failure occurrs. The timing chart for the start sequence logic is shown in figure 8.

A select signal must be provided in the dual-channel fuel control which allows either the fluidic or the electronic control to start the engine. The fluidic circuit for the start sequence logic is shown in figure 9. Functionally, it is the same as the electronic start sequence logic circuit.

There are two areas of concern in the fluidic start sequence logic circuit. The first is the low hysteresis bistable amplifier and the second is the delay circuit as shown in figure 10.

3. FLUIDIC SPEED GOVERNOR ON AIR TURBINE STARTER MODEL ATS500-1

3.1 Background. As mentioned in the preceeding introduction, Phase III of the dual-channel fuel control was revised to develop the fluidic speed governor and demonstrate it on Gas Turbine Starter Model ATS500-1. The goal was to apply the recently developed laminar fluidic speed sensor.

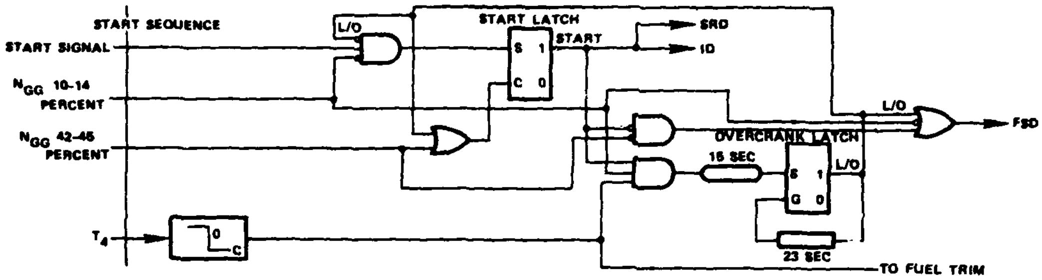


Figure 7. Electronic start sequence logic for ITI-GT601 gas turbine engine.

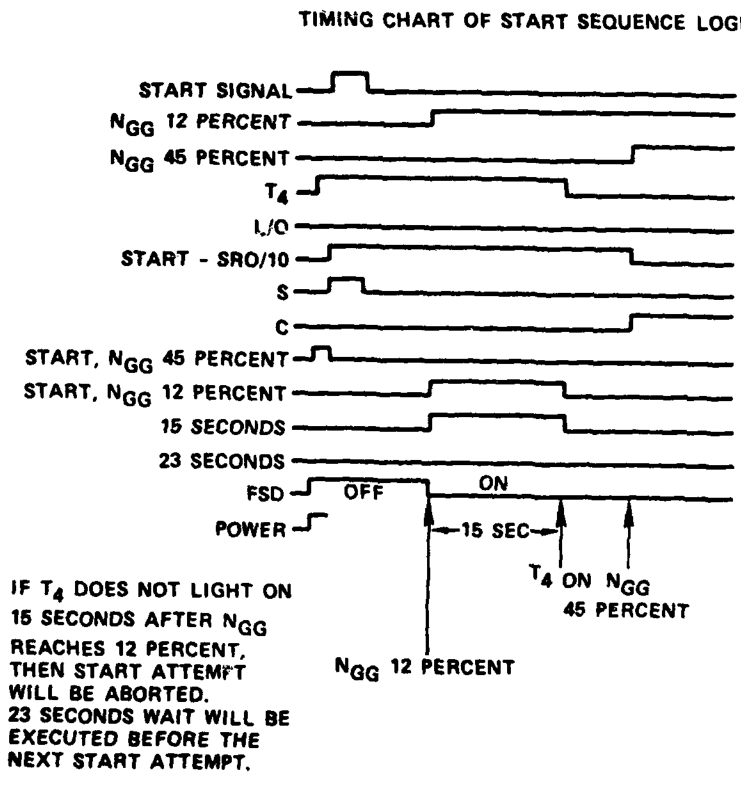


Figure 8. Timing chart for the start sequencing logic circuit.

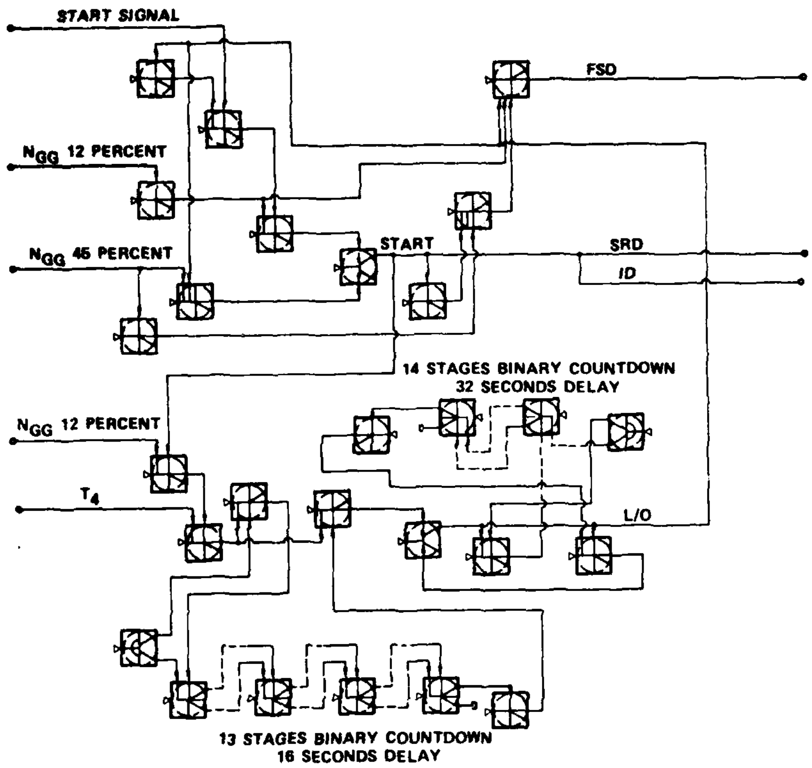


Figure 9. Fluidic start sequence logic circuit for the ITI-GT601 dual-channel fuel control program.

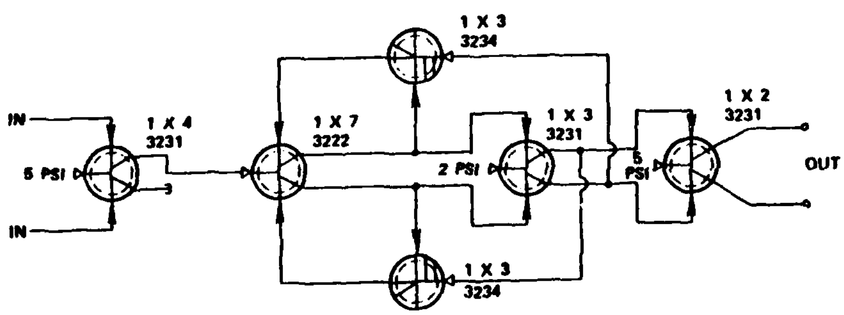


Figure 10. A binary countdown fluidic circuit.

Development of the speed governor is a necessary step for later application in the dual-channel fuel control since speed measurements are also required.

Starter Model ATS500-1 was chosen as the initial application of the fluidic speed sensor/governor because of two reasons. First, the unit was readily available for testing. Second, a different type of speed governor was being used so that some comparison could be made with the fluidic speed governor.

3.2 Phase III Work Statement. The Phase III work statement is summarized as follows:

1. Develop laminar speed sensor components suitable for application to Starter Model ATS500-1.

2. Develop necessary fluidic circuits for signal amplification.

3. Design and develop a complete fluidic speed governor package.

4. Perform system test on Starter Model ATS500-1.

3.3 Air/Gas Turbine Starter Model ATS500-1. Starter Model ATS500-1 was developed for the General Electric MS5002 turbine engine. Two or three starters are required to start the engine where each of the starters requires about 420 lb/min air at a typical inlet air pressure equal to 50 psig. The starter is rated for 500 hp output.

The cutaway drawing of Starter Model ATS500-1 is shown in figure 11. As shown in figure 11, the starter consists of the following major components: a control valve, a turbine, a gearbox, and a mechanical speed governor consisting of a flyweight speed sensor and a rotary servovalve.

The schematic of the starter is shown in figure 12. The operation of the starter is based on single, closed-loop control. Referring back to figure 12, the inlet port of the starter control valve is provided with a source of air or gas at some predetermined pressure limits. Filtered air or gas flows through the overpressure servo to the pressure regulator providing a reference pressure level for the pneumatic control valve actuator. Air or gas from the regulator then passes through the rotary servo valve, the rate control orifice, and then into the control valve which forces the butterfly to the open positon, allowing gas or air to flow through the turbine. The turbine shaft speed is reduced by the gearbox and transformed to lower drive shaft speed which is used to rotate and accelerate a gas turbine engine.

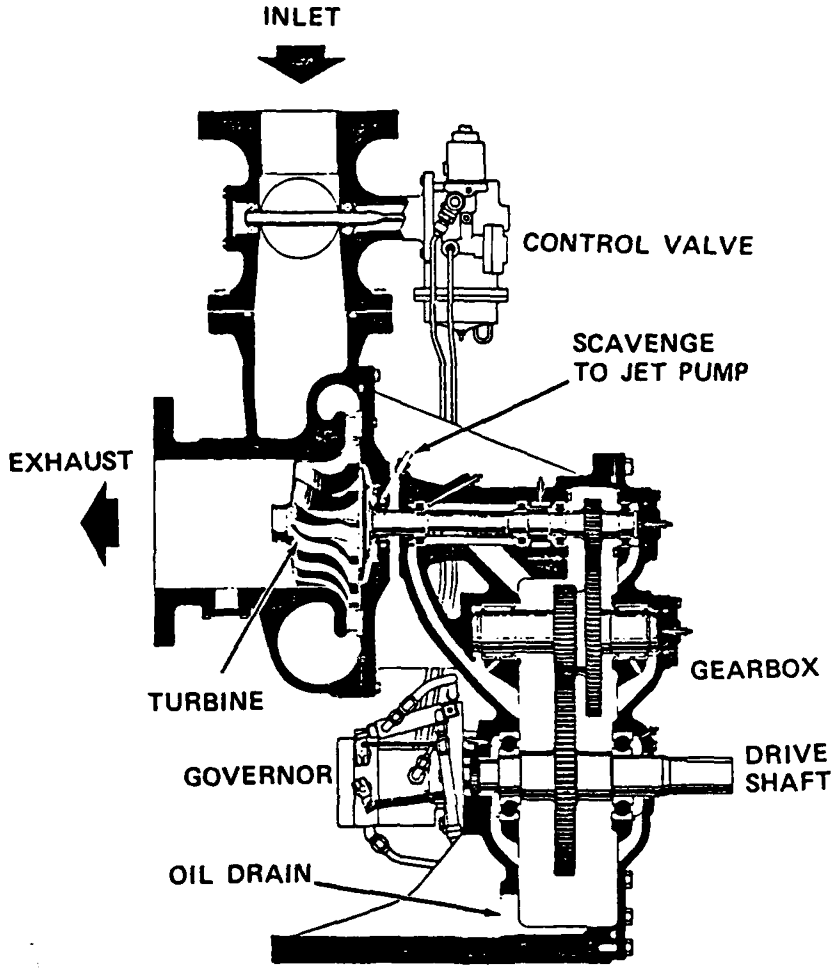


Figure 11. ATS500-1 starter cutaway drawing.

The flyweight speed sensor positions the rotary valve as a function of speed change at the predetermined set point. The rotary valve, in turn, modulates the pressure to the control valve.

A two-way solenoid valve is used to select the speed set point. When the solenoid is energized, the governor is reset to control at the high speed point. The overpressure control valve is provided so that the control valve will automatically close when a predetermined differential pressure across the valve and the turbine exceeds the normal maximum operating limit.

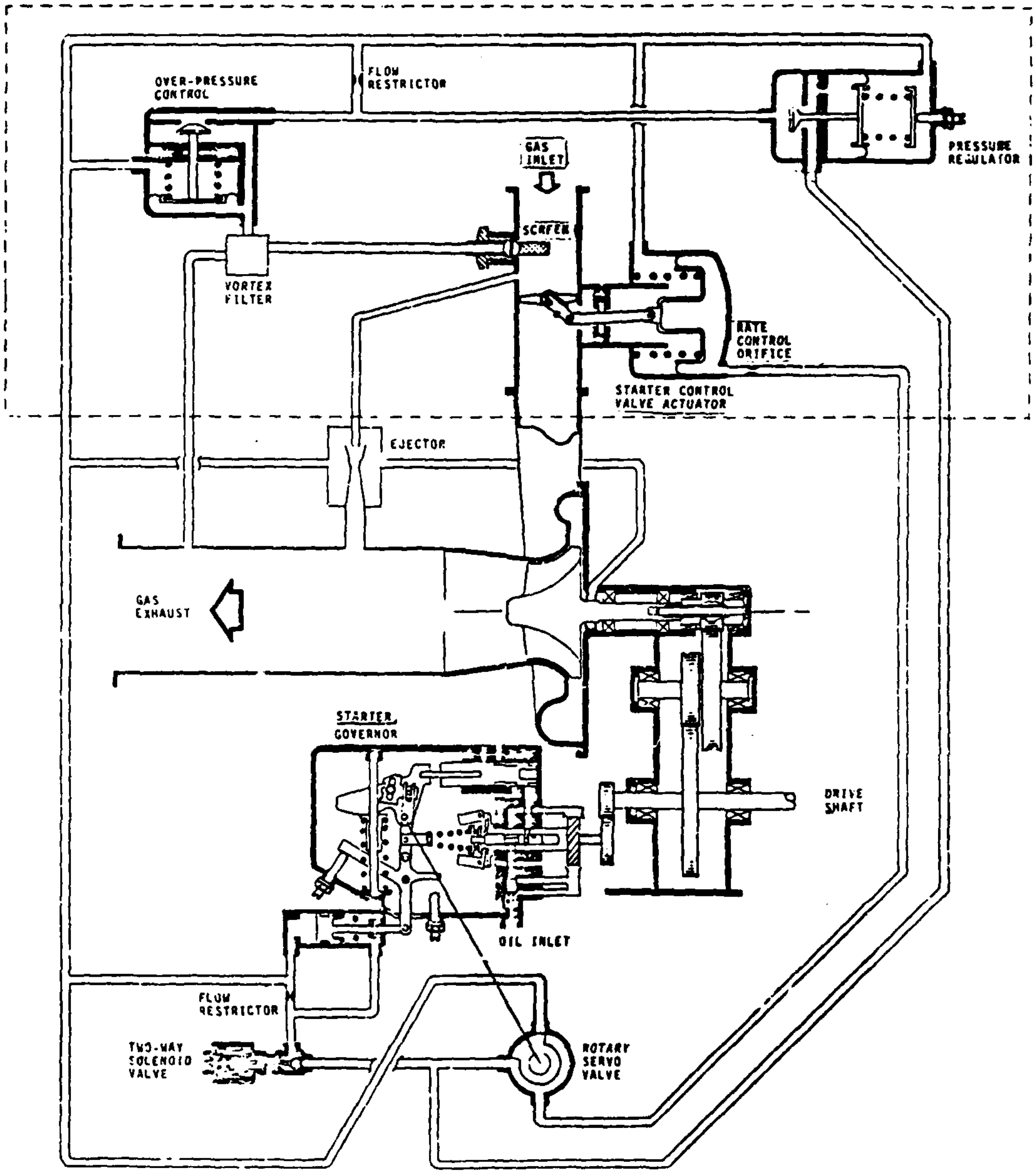


Figure 12. ATS500-1 starter schematic diagram.

3.4 Fluidic Speed Governor. The fluidic speed governor for Starter Model ATS500-1 was developed to be a direct replacement of the mechanical speed governor. The block diagram of Starter Model ATS500-1 with the fluidic speed governor is shown in figure 13. Figure 14 shows details of the fluidic speed governor. The governor consists of a laminar fluidic speed sensor, a laminar gain circuit, a turbulent gain circuit, a servovalve, a 258.55 Torr regulator, a 3-way solenoid valve for the speed selector, two needle valves for the speed set point adjustments, and an additional needle valve for adjustment of the laminar circuit supply pressure.

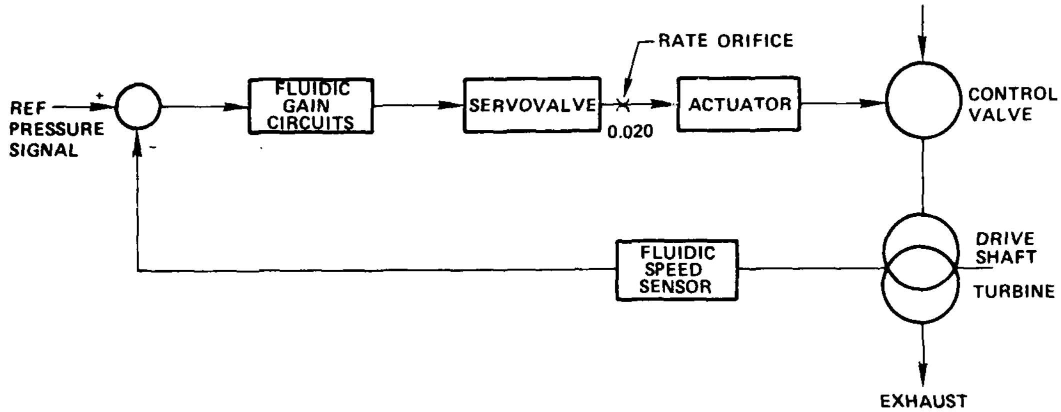


Figure 13. Block diagram of the ATS500-1 starter with fluidic speed governor.

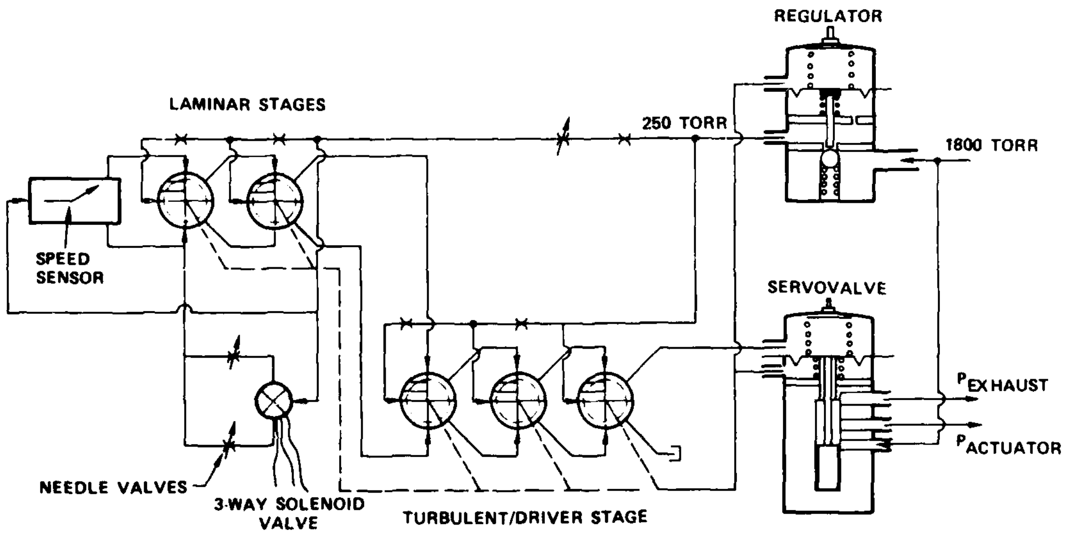


Figure 14. Schematic of the ATS500-1 starter fluidic speed governor.

3.5 Hardware Design

3.5.1 Design Objectives. The development of the fluidic speed governor for Starter Model ATS500-1 was initiated by formulating the design objectives which are summarized as follows:

TABLE III. DESIGN OBJECTIVES

Parameters	Design objectives values
Set points - low	1850 rpm ±100 rpm
- high	3700 rpm ±100 rpm
- adjustable band	±400 rpm at each set point
Working fluid	Air or natural gas
Operating temperature	Minus 65 F to 130 F
Ambient pressure	207 Torr to minus 259 Torr
Leakage	None allowed when using natural gas
Regulated pressure	1810 Torr ±103 Torr
Air/gas consumption	~500 lb/min at 2585 Torr inlet
Control valve	Normally closed (zero Torr input); requires 1551 Torr input for fully opened

3.5.2 Fluidic Manifold. The complexity of interconnecting the fluidic circuits, the laminar speed sensor, and the other components of the fluidic speed governor including the servovalve, the regulator, and needle valves raised some design problems. The initial approach was to house all components in an aluminum manifold block. However, due to complexity in the porting and the probable high fabrication cost, this approach was not considered further.

The final configuration has an aluminum block which houses the regulator, the servovalve, and the laminar speed sensor. In addition, a fluidic laminate manifold and a separate needle valve plate were used to greatly simplify the porting problem. The buildsheet for the laminated manifold is found in appendix A.

3.5.3 Laminar Speed Sensor. The laminar speed sensor is a relatively new concept for sensing speed. The operation of the sensor is similar to the proportional amplifier where the one side of its nozzle and receiver region is exposed to ambient through a slit. The amplifier is placed on top of a rotating shaft (roller) with a clearance of about 0.010 to 0.015 in. as shown in figure 15. As the shaft rotates, by friction, the air or any fluid around the shaft will travel with a speed which is proportional to the shaft speed. The power jet in the amplifier is deflected through the slit by the induced flow in which a differential output pressure can be sensed at the amplifier output ports. The output pressure is also proportional to the shaft speed. The suppressor is usually used to limit the boundary layer growth so that laminar flow can be maintained even at higher speed.

The laminar speed sensor for the speed governor on Starter Model ATS500-1 was constructed with the following configurations:

TABLE IV. LAMINAR SPEED SENSOR CONFIGURATION

Parameters	Values
Roller diameter	1.25 in.
Gap	0.010 in.
Supply pressure	4 Torr
Test range	Zero to 6500 rpm
Amplifier	(See appendix C for buildsheet)

The speed sensor was tested for its sensitivity and temperature effect. The sensor output and the parameters presented above are shown in figure 16 which shows the sensitivity equal to 0.1 Torr/1000 rpm.

Figure 17 shows the sensor noise level at about 3000 rpm where the output scale is amplified by 10. From the data, the signal-to-noise (S/N) ratio is calculated to be 67 per 1000 rpm compared to the chopper/digital speed sensor S/N ratio of 30 per 1000 rpm.

After the speed sensor was installed, a temperature test was also performed. Figure 18 shows the test data. A decrease in the sensitivity was noticed which also resulted in a decrease in the speed set point.

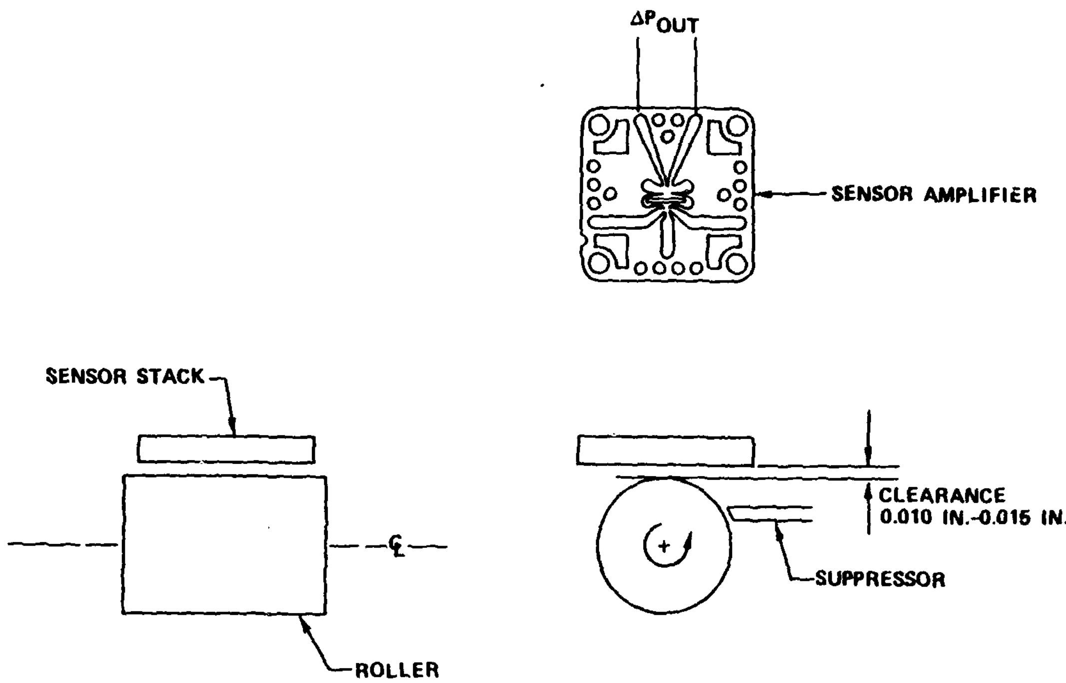


Figure 15. Laminar fluidic speed sensor.

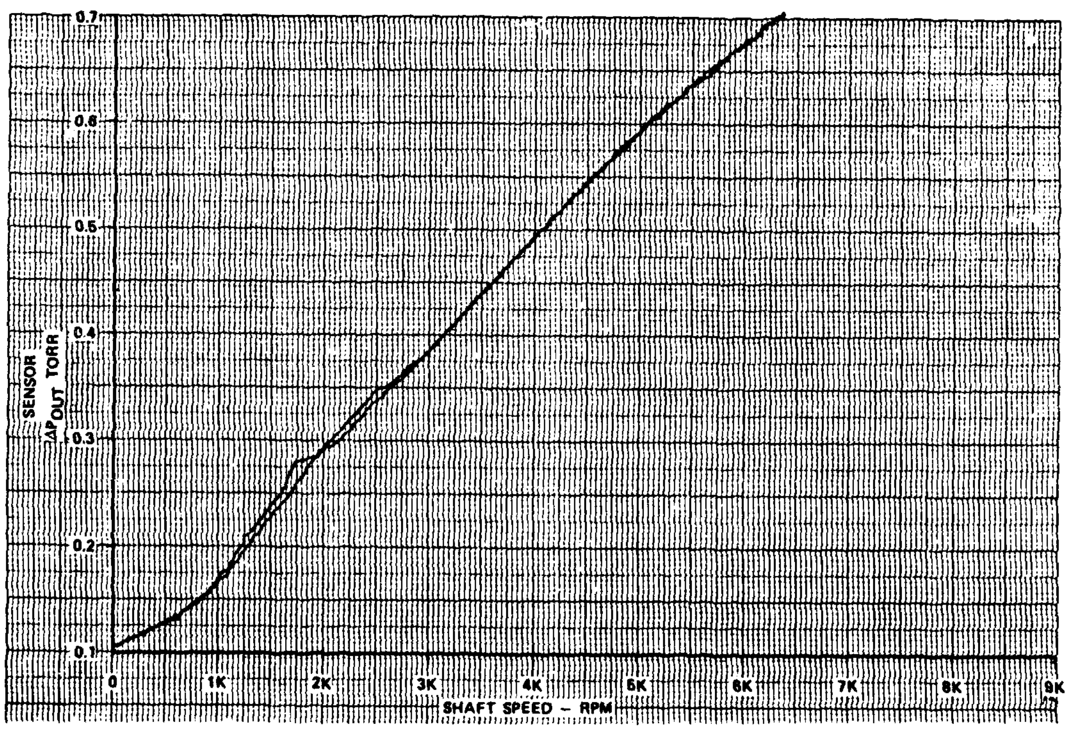


Figure 16. Laminar speed sensor performance.

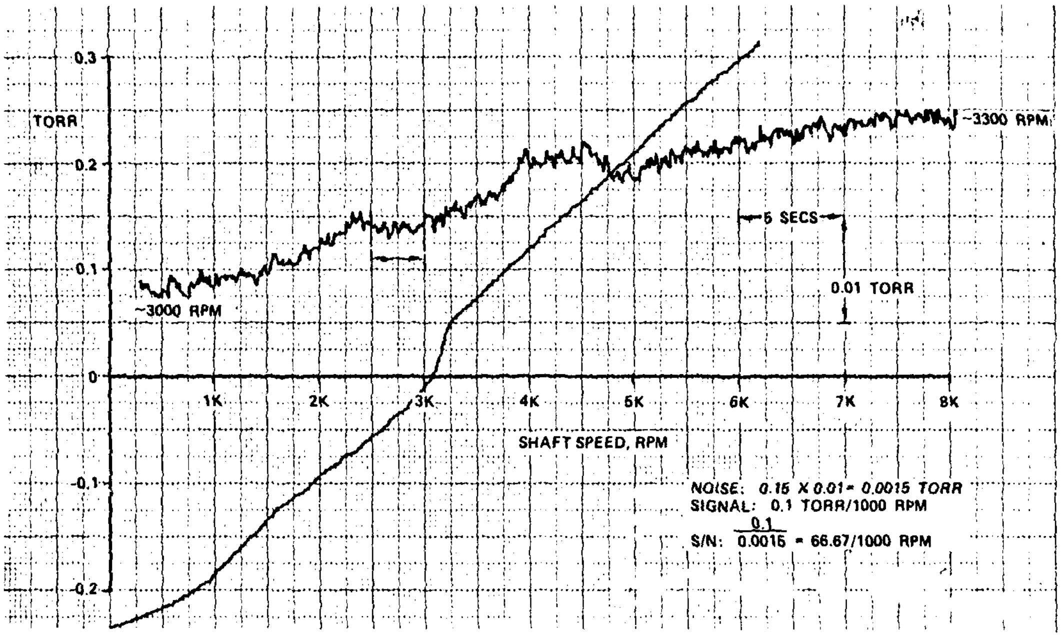


Figure 17. Laminar speed sensor noise measurement.

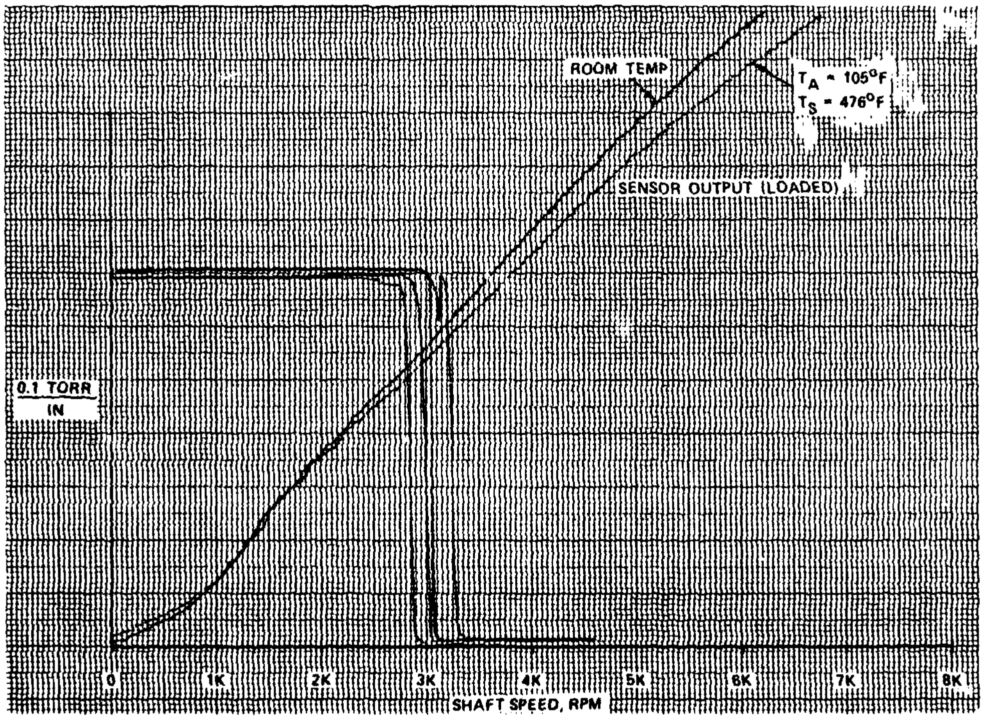


Figure 18. Laminar speed sensor hot gas test.

3.5.4 <u>Fluidic Gain Circuits</u>. The fluidic gain circuits for the governor consisted of the laminar and the turbulent gain circuits mounted on the fluidic manifold. Like the sensor amplifier, the gain circuits were built using only one type of fluidic laminate, designated as the C-format laminate. The C-format is commonly used in other applications for its practical size which is 1.31 in. x 1.31 in.

The schematic of the laminar gain circuit and its actual gain curve are shown in figure 19. As shown in figure 19, the laminar gain circuit has two stages. With a supply pressure of 10.5 torr, it has a gain of 40.

The turbulent gain circuit is shown schematically in figure 20 along with its gain curve. The circuit has a three-stage amplifier with a single-sided output used to drive the servovalve. As shown in figure 20, the overall gain of the circuit is about 27.7.

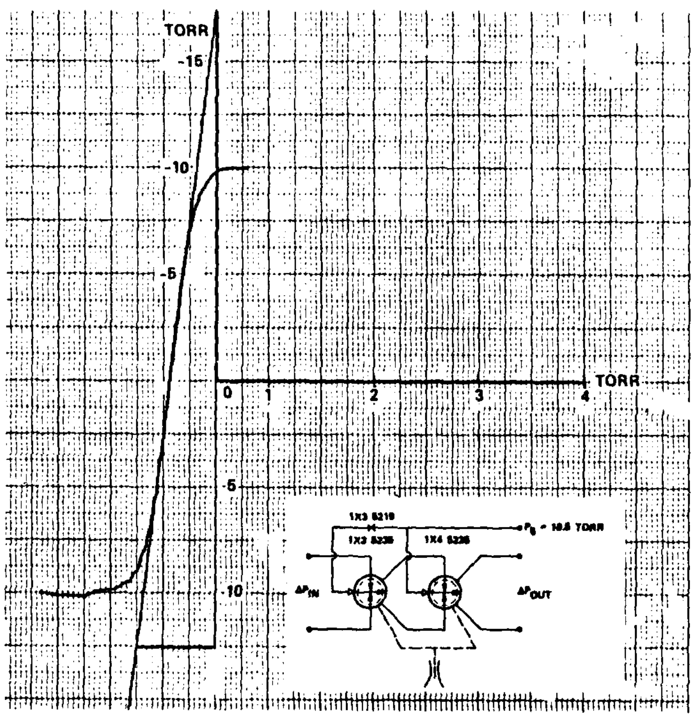


Figure 19. Laminar gain circuit.

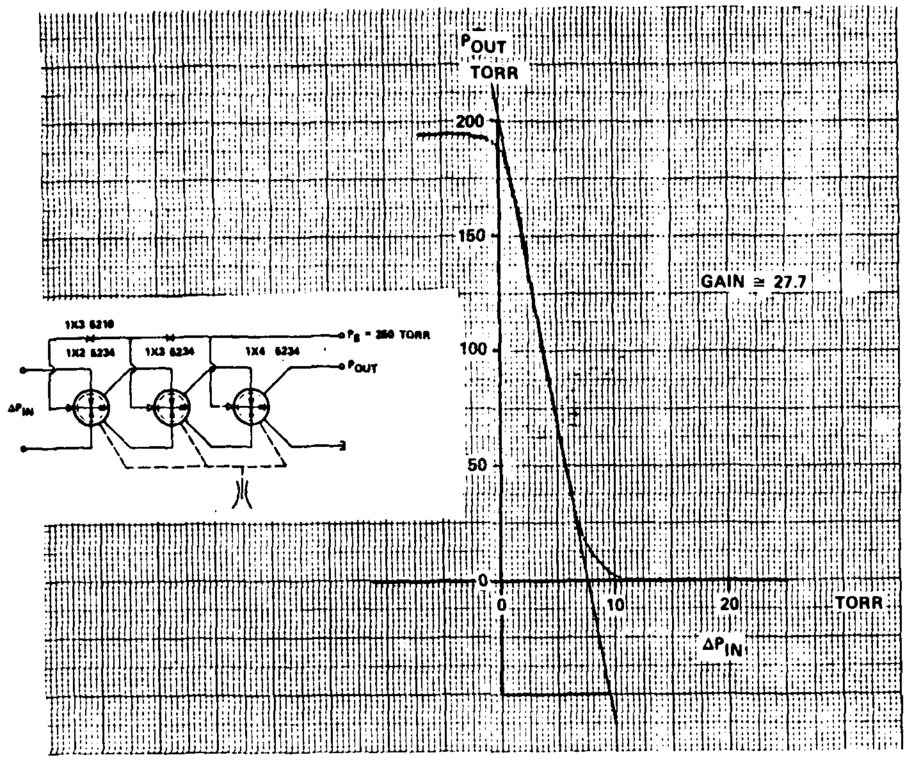
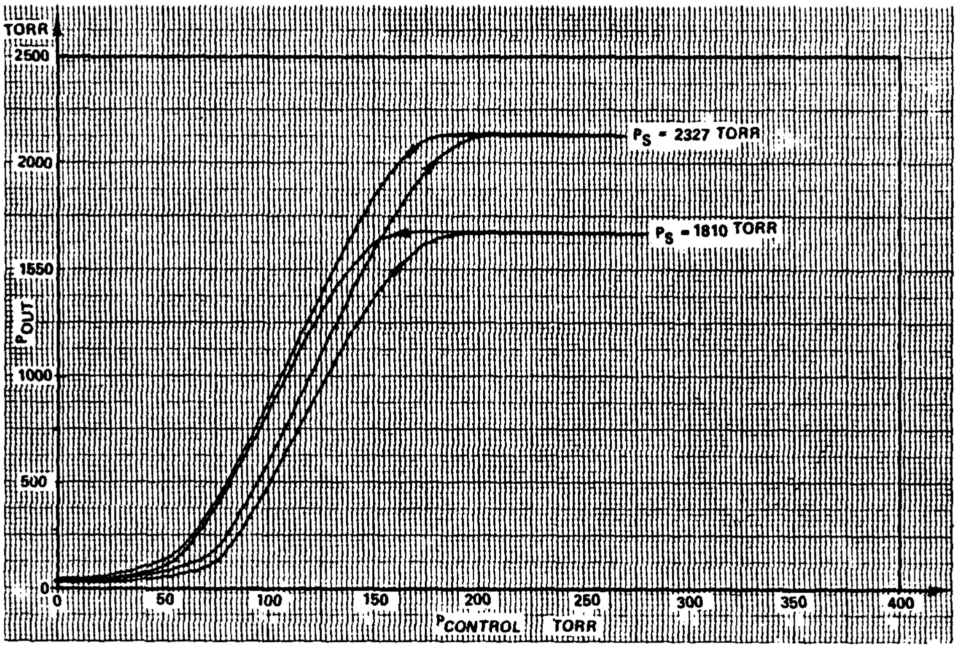


Figure 20. Turbulent gain circuit.

The stacking order lists of the laminar and the turbulent gain circuits are found in appendix C.

3.5.5 <u>Servovalve</u>. The actuator valve requires approximately 1499.59 Torr to activate it to the full open position, whereas the regulated supply pressure available at the starter is only 1809.85 Torr. Due to the high actuator pressure requirement, the actuator valve of the starter should be driven by a servovalve instead of directly by the fluidic gain circuits which typically have a pressure recovery of only 50 to 75 percent.

The servovalve designed for this purpose was a spool-type servovalve with output pressure feedback to reduce noise level (details of the servo are found in appendix D). The servo has some hysteresis which is about 15.513 Torr at P_S = 18098.5 Torr. The hysteresis decreases with increasing supply pressure (see figure 21 for the test results on the servo).



ATS-600-1 SERVO

Figure 21. Servovalve gain curve.

3.6 Integrated Speed Governor. The fluidic speed governor assembly (which consists of the laminar speed sensor, two gain blocks, the manifold, the servovalve, the fluidic regulator, and the adjustment orifice plate) is assembled on the aluminum block. An adapter plate was attached to the block to mount the governor to the starter. Photos of the assembled speed governor are shown in figures 22 and 23.

3.7 System .est. The governor was bench tested and calibrated before it was tested on the starter. The two speed set points were set at about 2100 rpm for low speed and 4200 rpm for high speed. The unit also showed a hysteresis of about 200 rpm. Figure 24 shows the calibration curve.

The installation of the fluidic speed gcvernor on the starter is shown in figures 25 and 26. In this test setup, the actual engine load during the start cycle was simulated with the flywheel (see figure 27) and a dynamometer which allows high torque at low speed and low torque at high speed.

The instrumentation was set up to measure the output shaft rpm, the output torque, the inlet pressure, the exhaust pressure, the pressure to the control valve, and the inlet air temperature. The data were taken using an 8-channel chart recorder.

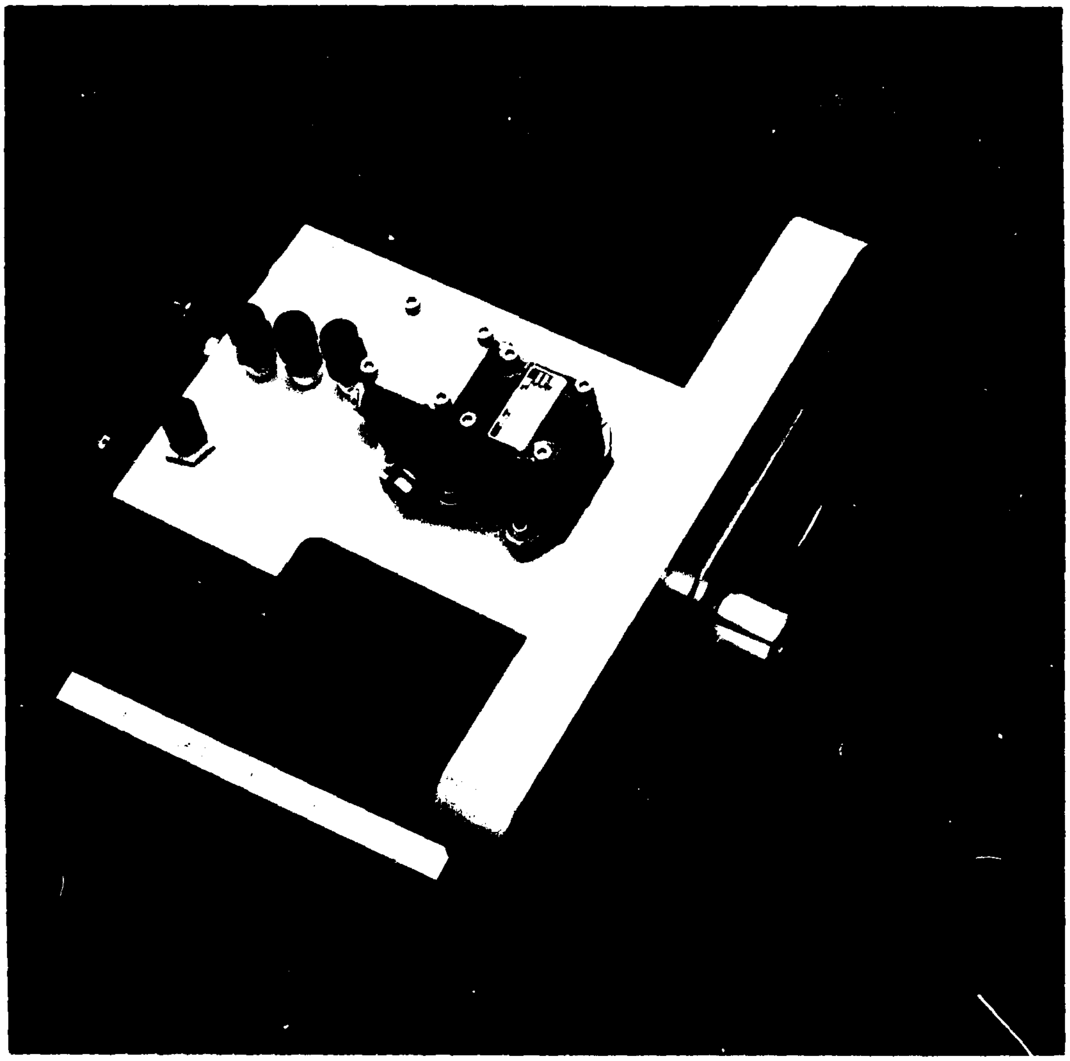


Figure 22. Fluidic speed governor 3/4 view.

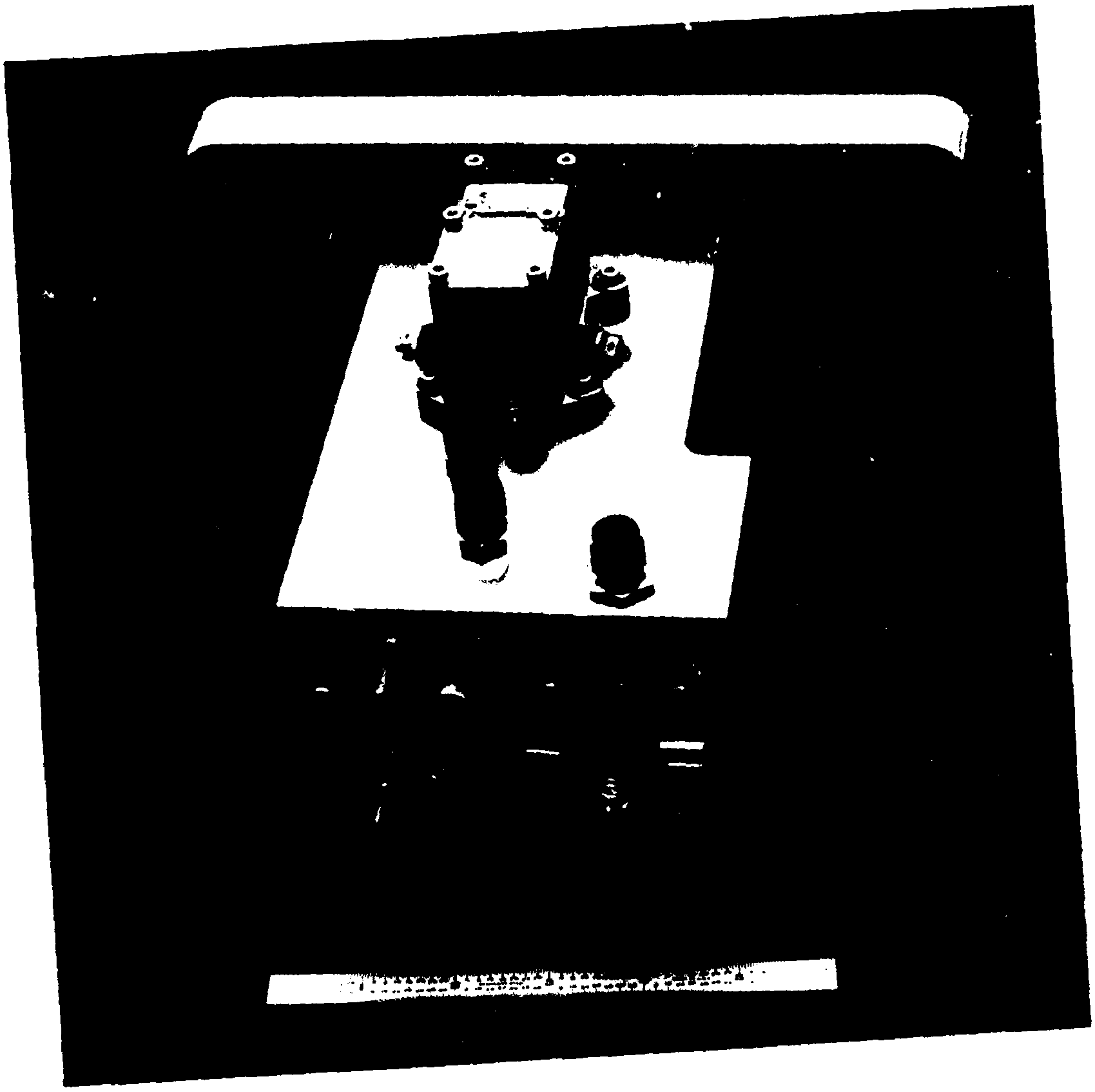


Figure 23. Fluidic speed governor front view.

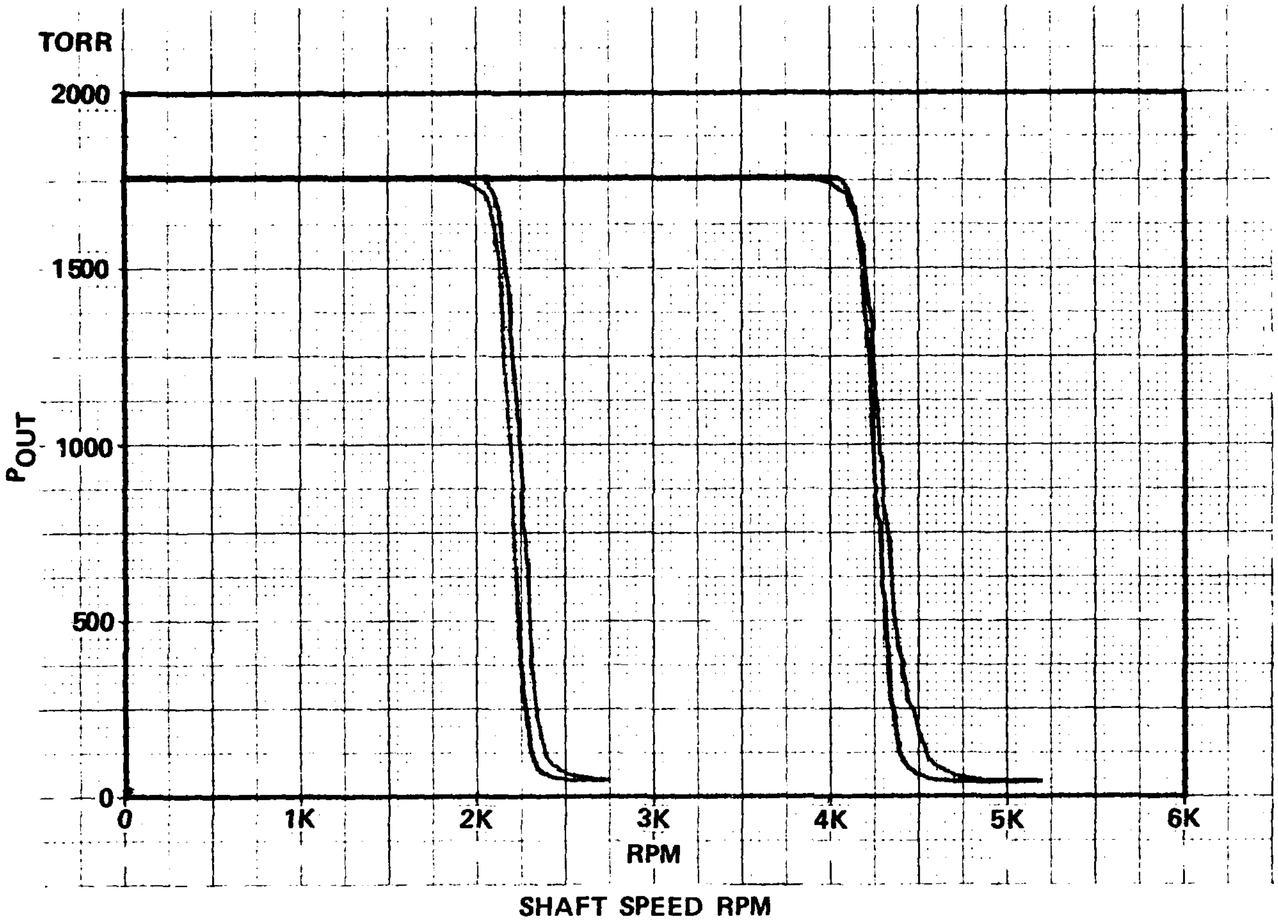


Figure 24. Calibration curve.

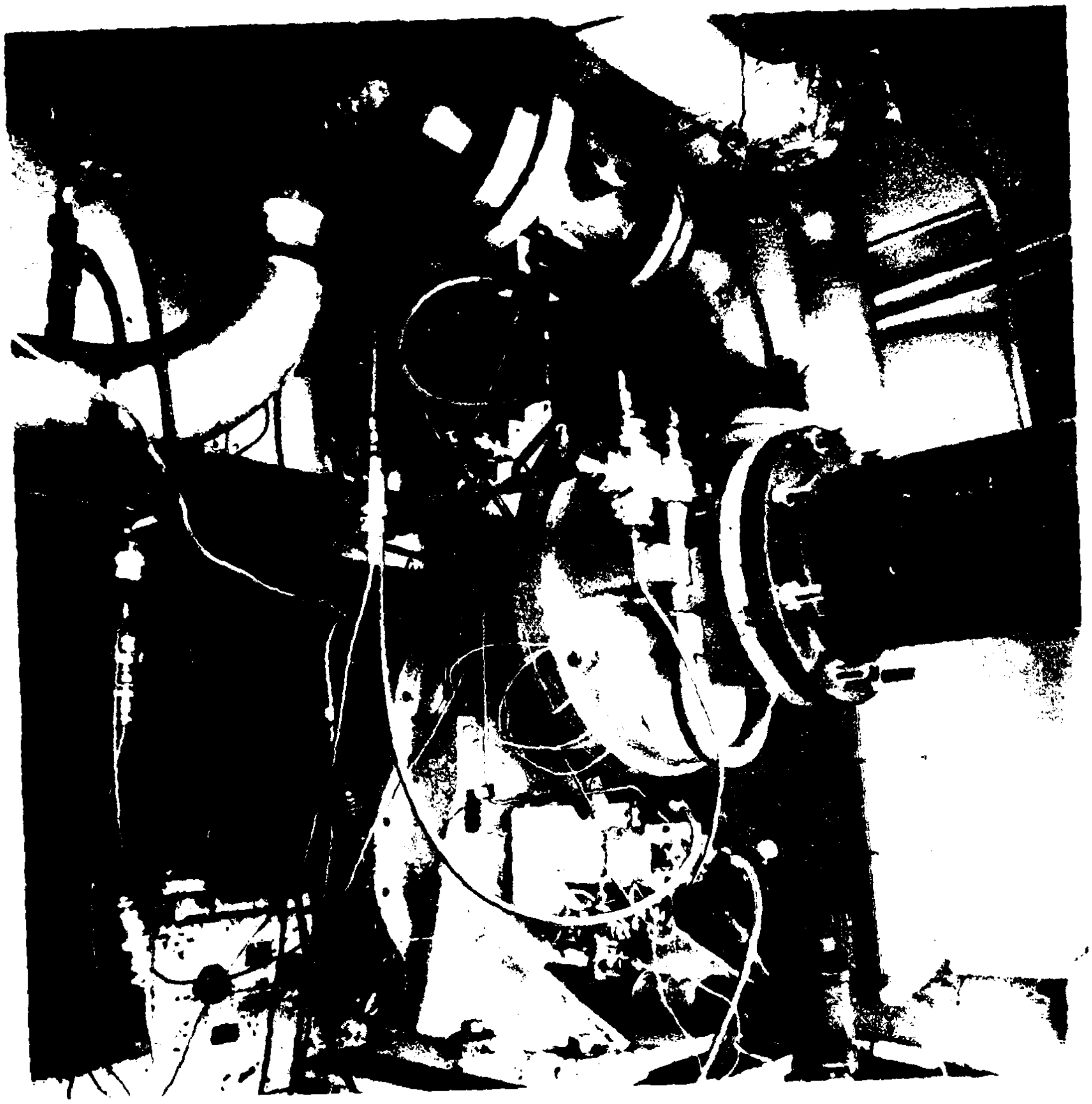


Figure 25. Starter Model ATS500 installation.

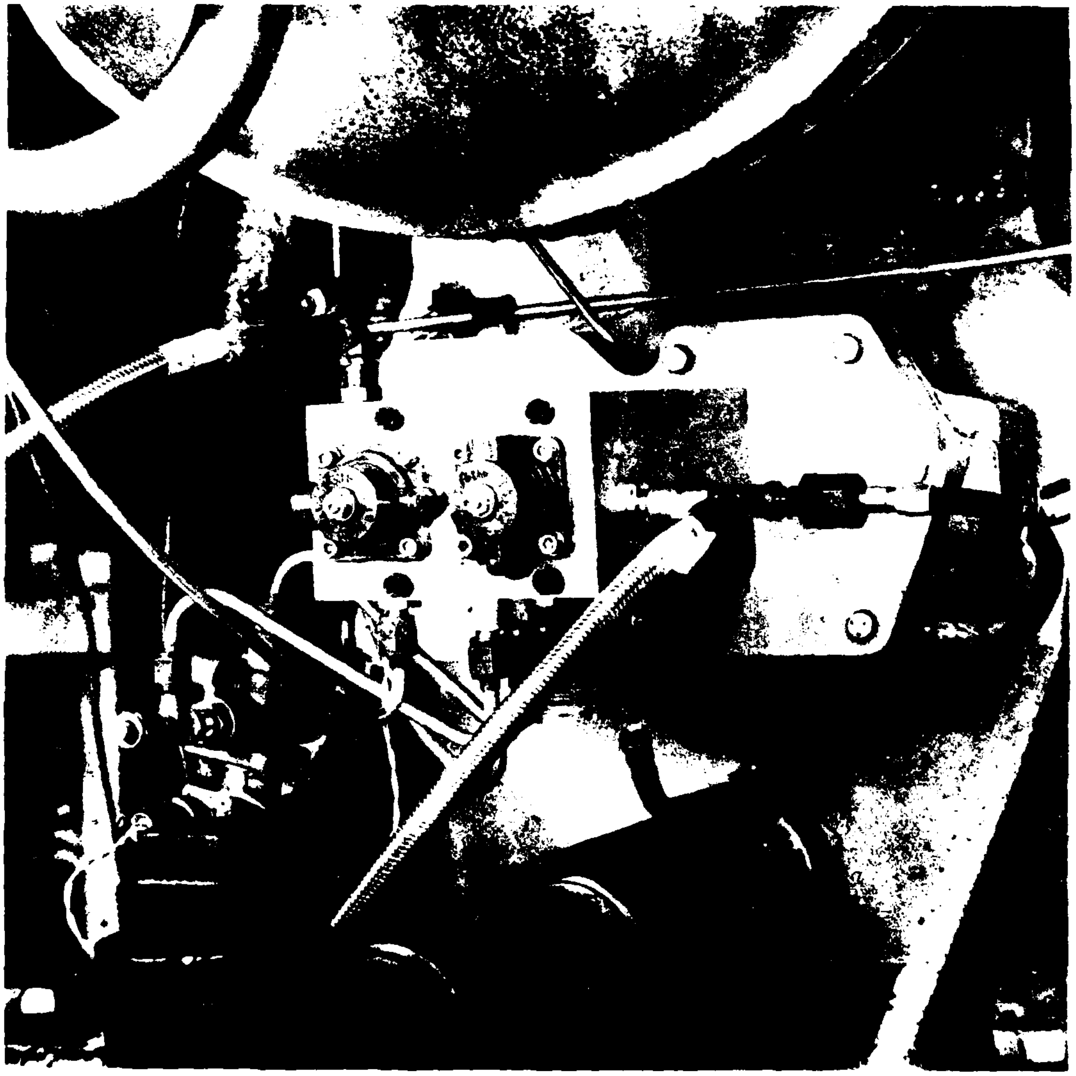


Figure 26. Fluidic speed sensor installed on starter.

PMP-01124

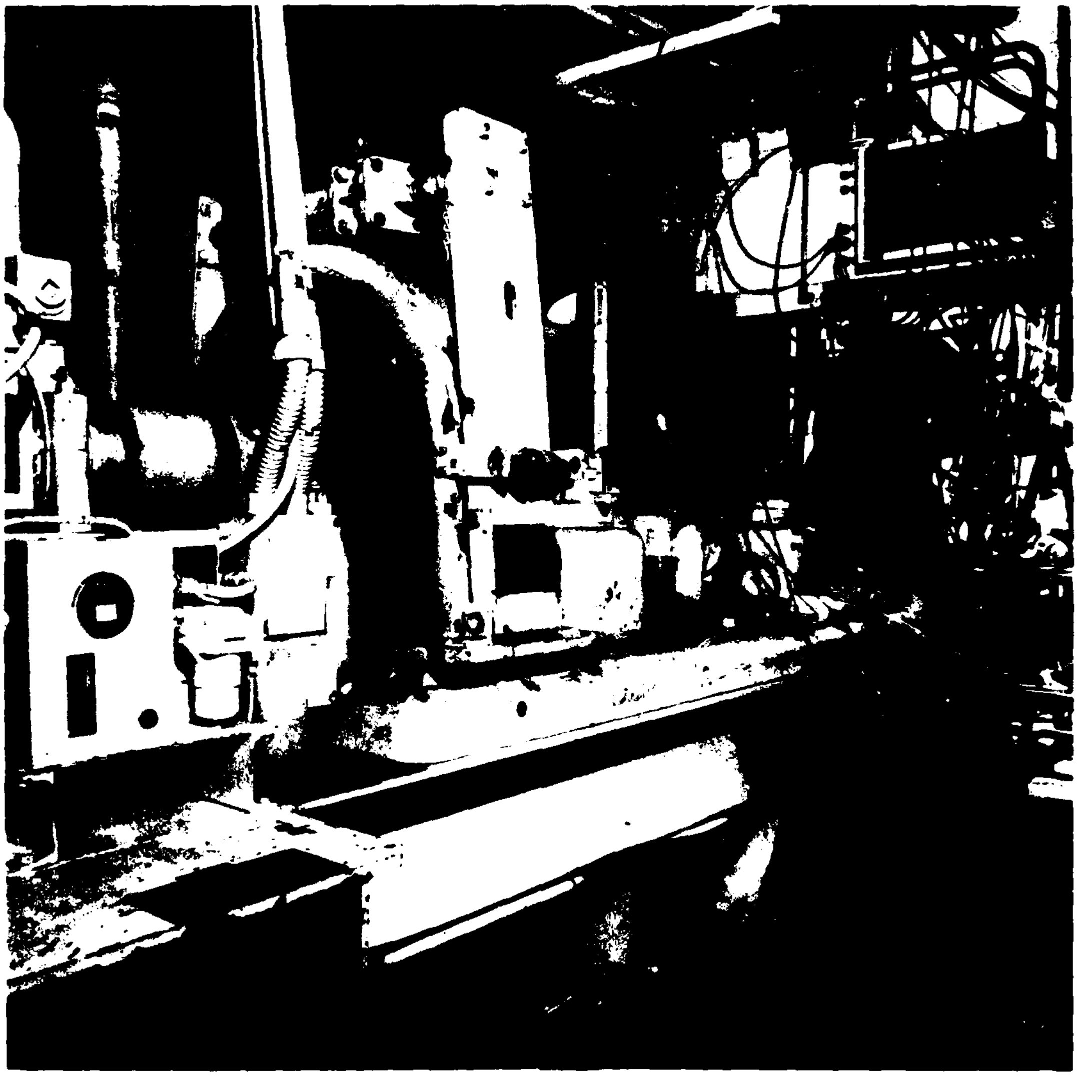


Figure 27. Fluidic speed sensor test setup.

3.8 Test Results. The final test data of the fluidic speed governor is shown in figure 28. Figure 29 shows the test data of the starter with the mechanical speed governor.

As seen in figure 28, the fluidic speed governor shows stable control of the starter at both speed set points. The only problem in the results is that the output of the governor which drives the control valve is somewhat more noisy during the initial start cycle. This may be due to the fact that the laminar speed sensor is sensitive to low frequency vibration.

4. CONCLUSIONS

In the GT601 dual-channel fuel control, the fluidic devices have been shown to be a viable replacement for the electronic counterparts. During Phase III of this program, preliminary interface, sensors, and a start logic circuit have been outlined to implement a simplified dual-channel fuel control.

A full-scale development effort for Phase III of the dual-channel fuel control program was not achieved due to the revision of the program task.

The revised task for Phase III was to demonstrate a speed governor on Starter Model ATS500-1 using the laminar speed sensor. The system test on Starter Model ATS500-1 has shown that the laminar speed sensor can be used for closed-loop speed control application. The advantages and disadvantages of the sensor were identified to be the following:

Advantages of Laminar Speed Sensor

- Does not require a frequency-to-analog conversion circuit
- Has a higher signal-to-noise ratio than the chopper speed sensor
- Provides directionality sensing
- Easy mechanical-pneumatic interface

Disadvantages of Laminar Speed Sensor

- More susceptible to supply pressure variation
- More sensitive to vibration generated noise

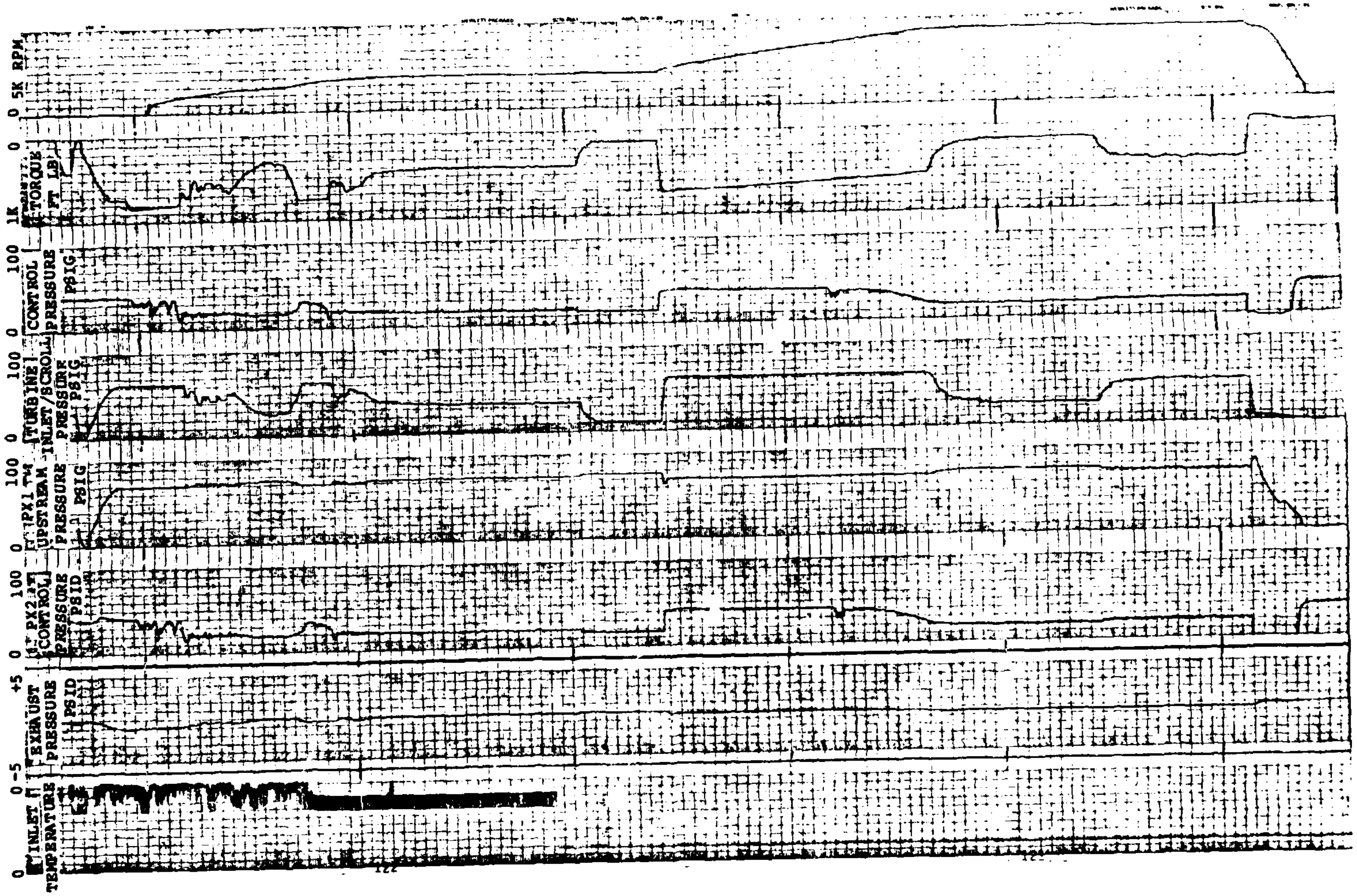


Figure 28. Fluidic speed governor test data.

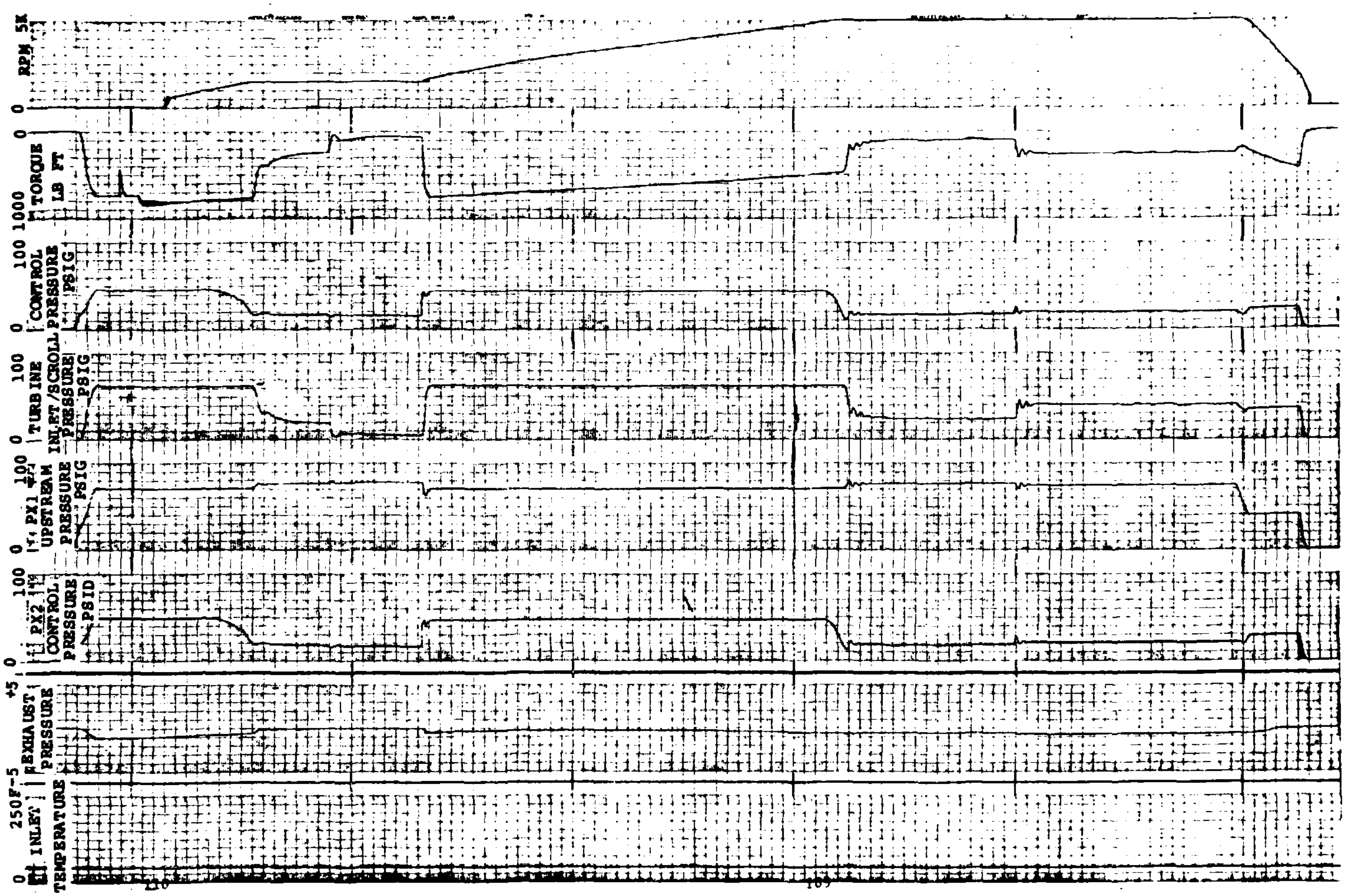


Figure 29. Mechanical flyweight speed governor test data.

5. RECOMMENDATIONS

Further studies of the sensors and the start logic circuit to initiate a full scale design and development effort are recommended. In the studies, the VTN and the fuel metering requirements (tasks in Phase V) should be given some considerations to ease system integration in the final system.

The laminar speed sensor has been shown to have some potential applications although there are still areas of concern, such as vibration sensitivity. To improve the sensor for application where vibration may exist, subsequent development efforts are recommended.

APPENDIX A - FLUIDIC MANIFOLD BUILDSHEET

The fluidic manifold was used to mount the two C-format size gain circuits on its top. The speed sensor amplifier was attached on one of its bottom sides.

Figure A-1 shows the stacking order and quantity required for each type of laminate. Each laminate has a thickness of 0.020 in. and the overall thickness of the manifold is about 0.360 in.

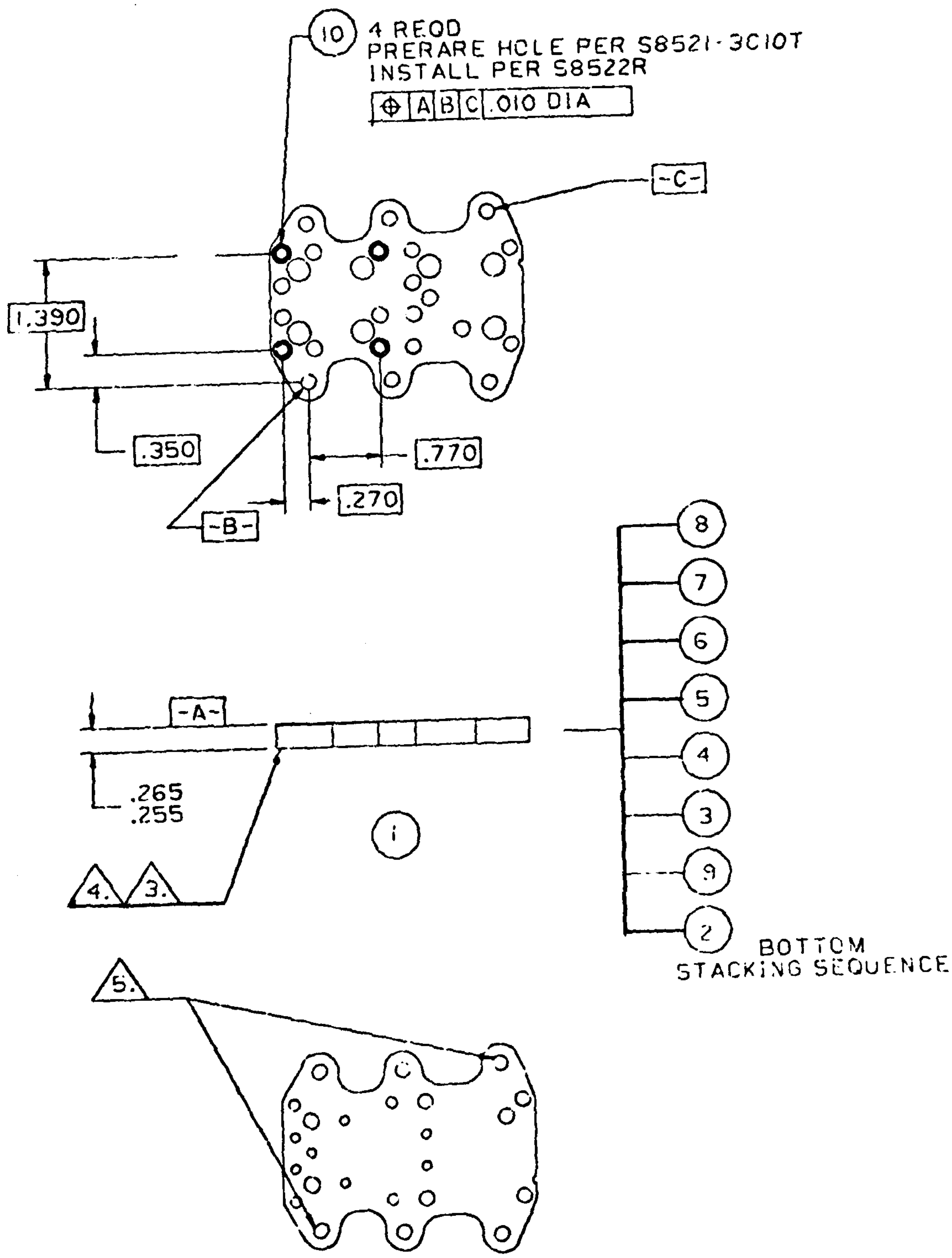


Figure A-1. Fluidic manifold stocking.

APPENDIX B - LAMINAR SPEED SENSOR BUILDSHEET

The main part of the laminar speed sensor is its amplifier which is shown in figure B-1. The laminar amplifier was designed on a C-format size laminate; however, its orientation is 45 degrees off from the normal C-format amplifier.

The stacking order of the sensor is shown in figure B-2. The port plate laminate has a narrow straight hole in its center and the laminate was modified by hand. A gasket plate made of Part 3155040 was also needed to get the proper clearance between the sensor and the roller shaft. (This is not shown in the buildsheet.)

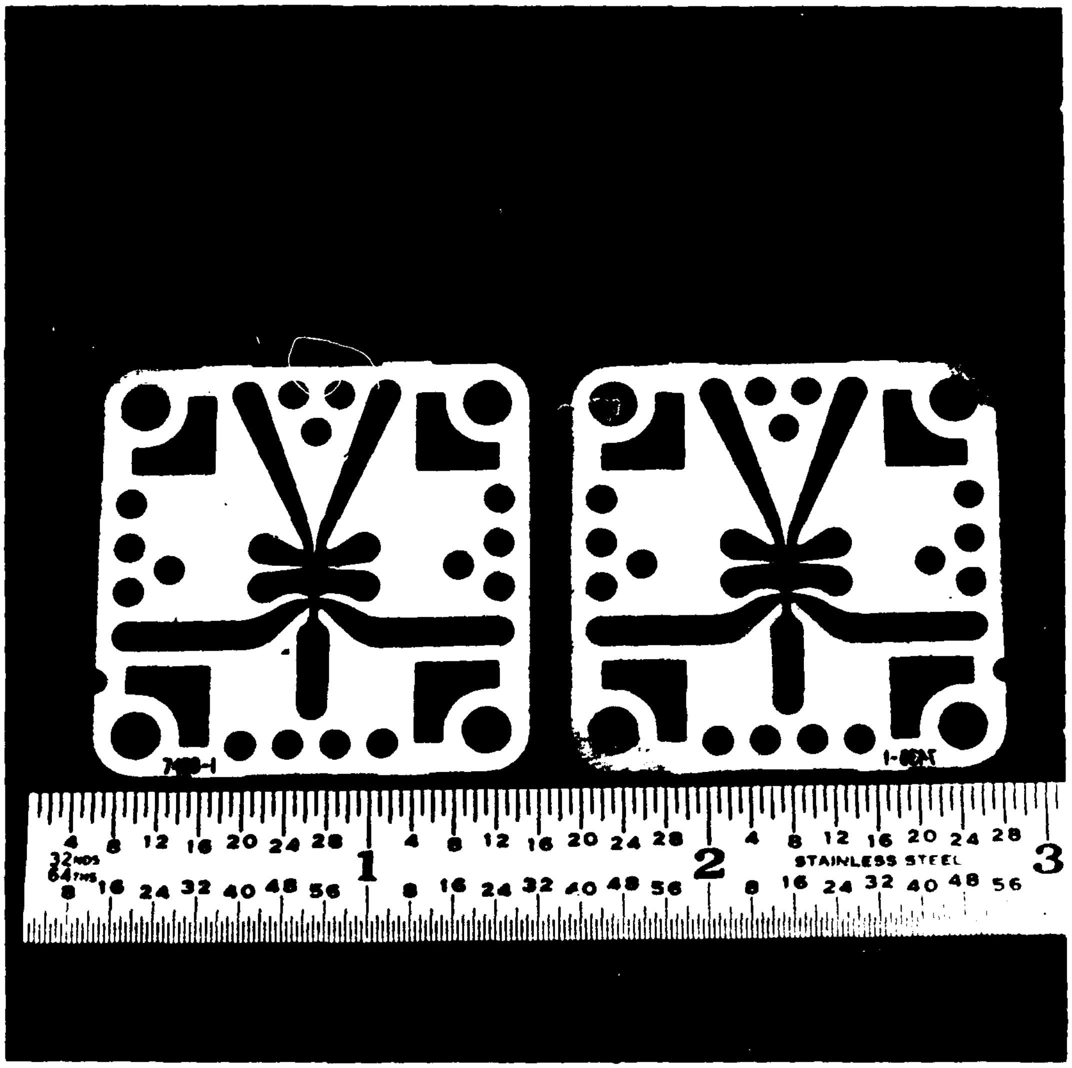
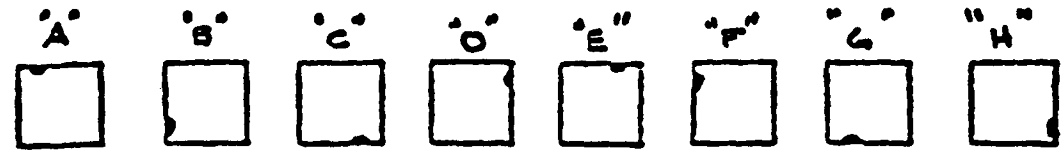


Figure B-1. Sensor amplifier

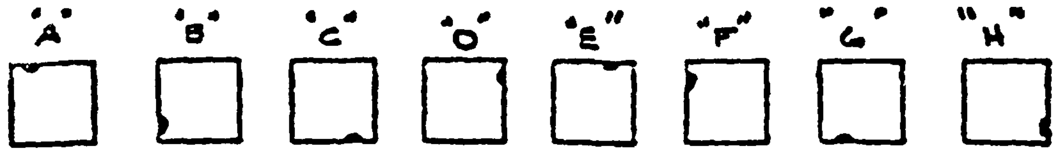


STACK SEQ	PART NUMBER	△	DESCRIPTION	QUAN. REQ'D	REMARKS
1	3155185	A	PORT PLATE	1	MODIFIED
2	3157438	A	AMPLIFIER	3	
3	3155189	A	VENT	1	
4	3155198	A	EXHAUST	3	
5	3155021	B	GASKET (6)	1	
6	3155114	C	TRANSFER	3	
7	3155042	A	G	2	
8	3155040	A	G	1	

Figure B-2. Sensor stacking order.

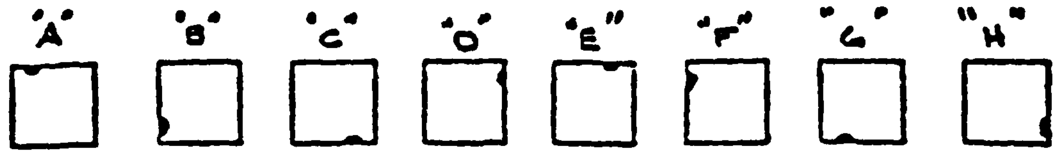
APPENDIX C - GAIN CIRCUITS BUILDSHEET

The laminate stacking order for the laminar and the turbulent gain circuits is shown in figures C-1 and C-2, respectively. In the buildsheets, several laminates have been designated with "M" which means that the laminates were hand tool modified to add extra holes or transfer holes.



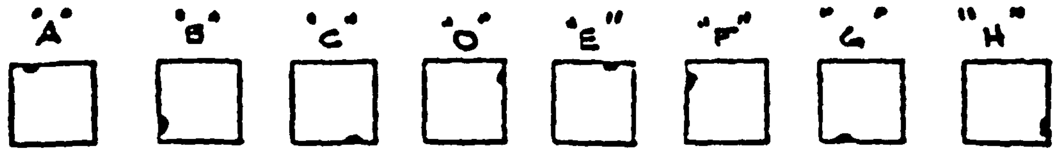
STACK SEQ	PART NUMBER	△	DESCRIPTION	QUAN. REQ'D	REMARKS
1	3155034	B	GASKET (G)	1	
2	3155033	B	TRANSFER (T)	3	
3	3155005	B	FILTER (F)	1	
4	3155033	B	T	3	
5	3155018	B	G	1	
6	3155021	D	G	1	
7	3155045	D	G	1	
8	3155045	A	G	1	
9	3155044	D	G	1	
10	3155044	A	G	1	
11	3155021	C	G	1	
12	3155216	G	T	1	
13	3155219	G	ORIFICE (O)	1	
14	3155216	G	T	1	
15	3155219	G	O	1	
16	3155216	G	T	1	
17	3155018	B	G	1	
18	3155021	A	G	1	
19	3155018	B	G	1	
20	3155198	B	EXHAUST (E)	2	
21	3155237	D	E	1	
22	3155236	D	VENT (V)	1	
23	3155235	D	AMPLIFIER (A)	4	
24	3155236	D	V	1	
25	3155237	D	E	1	
26	3155198	B	E	2	
27	3155018	D	G	1	
28	3155021	D	G	1	
29	3155022	A	G	1	

Figure C-1. Laminar gain circuit stacking order.



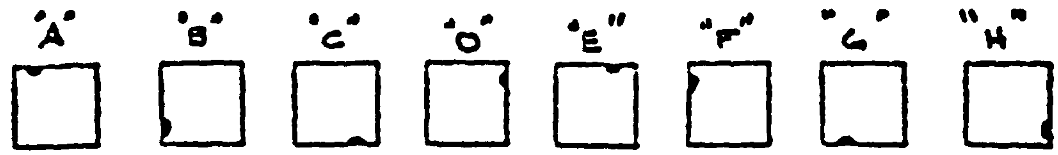
STACK SEQ	PART NUMBER	△	DESCRIPTION	QUAN. REQ'D	REMARKS
30	3155217	D	T	1	
31	3155219	B	O	1	
32	3155217	D	T	1	
33	3155219	B	D	1	
34	3155217	D	T	1	
35	3155219	B	O	1	
36	3155217	D	T	1	
37	3155018	D	G	1	
38	3155021	B	G	1	
39	3155198	B	E	2	
40	3155237	B	E	1	
41	3155236	B	V	1	
42	3155235	B	A	3	
43	3155236	B	V	1	
44	3155237	B	E	1	
45	3155198	B	E	2	
46	3155018	B	G	1	
47	3155022	A	G	1	
48	3155110	G	T	2	
49	3155115	C	T	2	
50	3155019	A	G	1	

Figure C-1. Laminar gain circuit stacking order (Concluded).



STACK SEQ	PART NUMBER	△	DESCRIPTION	QUAN. REQ'D	REMARKS
1	3155019	C	GASKET (G)		"M"
2	3155033	C	TRANSFER (T)	3	"M"
3	3155005	C	FILTER (F)	1	
4	3155033	C	T	3	"M"
5	3155041	C	G	1	
6	3155114	D	T	2	
7	3155021	B	G	1	
8	3155018	A	G	1	
9	3155108	B	T	2	
10	3155191	F	T	2	
11	3155018	C	G	1	
12	3155215	D	T	1	
13	3155219	D	ORIFICE (O)	4	
14	3155215	D	T	1	
15	3155116	D	T	2	
16	3155044	D	G	1	
17	3155110	D	T	2	
18	3155116	E	T	2	
19	3155045	C	G	1	
20	3155045	B	G	1	
21	3155042	A	G	1	
22	3155018	D	G	1	
23	3155114	A	T	2	
24	3155021	C	G	1	
25	3155021	B	G	1	
26	3155045	B	G	1	
27	3155045	C	G	1	
28	3155044	D	G	1	
29	3155108	A	T	2	
30	3155041	A	G	1	

Figure C-2. Turbulent gain circuit stacking order.



STACK SEQ	PART NUMBER	△	DESCRIPTION	QUAN. REQ'D	REMARKS
31	3155004	G	EXHAUST (E)	2	
32	3155000	G	VENT (V)	2	
33	3155234	G	AMPLIFIER (A)	4	
34	3155000	G	V	2	
35	3155004	G	E	2	
36	3155018	B	G	1	
37	3155217	B	T	1	
38	3155219	D	O	4	
39	3155217	B	T	1	
40	3155021	D	G	1	
41	3155003	D	E	2	
42	3155000	D	V	2	
43	3155234	D	A	3	
44	3155000	D	V	2	
45	3155003	D	E	2	
46	3155018	D	G	1	
47	3155217	D	T	1	
48	3155219	B	O	1	
49	3155217	D	T	1	
50	3155040	A	G	1	
51	3155004	G	E	2	
52	3155000	G	V	2	
53	3155234	G	A	2	
54	3155000	G	V	2	
55	3155004	G	E	2	
56	3155018	B	G	1	
57	3155110	B	T	2	
58	3155116	B	T	2	
59	3155019	A	G	1	

Figure C-2. Turbulent gain circuit stacking order (Concluded).

APPENDIX D - SERVOVALVE DESIGN

The schematic of the servovalve is shown in figure-D-1 and the parameters used are listed in table D-1.

TABLE D-1

SERVOVALVE DESIGN PARAMETERS

Parameters	Values
Diaphragm effective area	A_D = 1.227 in.^{2}
Spool cross sectional area	A_S = 0.491 in.^{2}
Port diameter	d = 0.100 in.
Spring preload	F_S = 3.0 lb
Spring rate	k_1 = 15 lb/in.
Spring rate	k_2 = 10 lb/in.
Servo output pressure	P_A = 0-3.5 psid
Fluidic output pressure	P_C = 0-2.5 psid
Servo vent/exhaust pressure	P_E = 14.7 psia
Servo supply pressure	P_S = 35 psig
Fluidic vent pressure	P_V = 14.7 psia

The only calculation in the design of the servo was for the spring rates. This was done by the force balance equation assuming that all other parameters are known or assumed.

$$(k_1 + k_2)\ x\ + P_A A_S = (P_C - P_V) A_D$$

x = maximum stroke fully closed to fully opened = 0.050 in.

$$(k_1 + k_2)\ 0.050\ \text{in.} + 35 \times 0.0491 = 2.5 \times 1.227$$

$$k_1 + k_2 = 26.98\ \text{lb/in.}$$

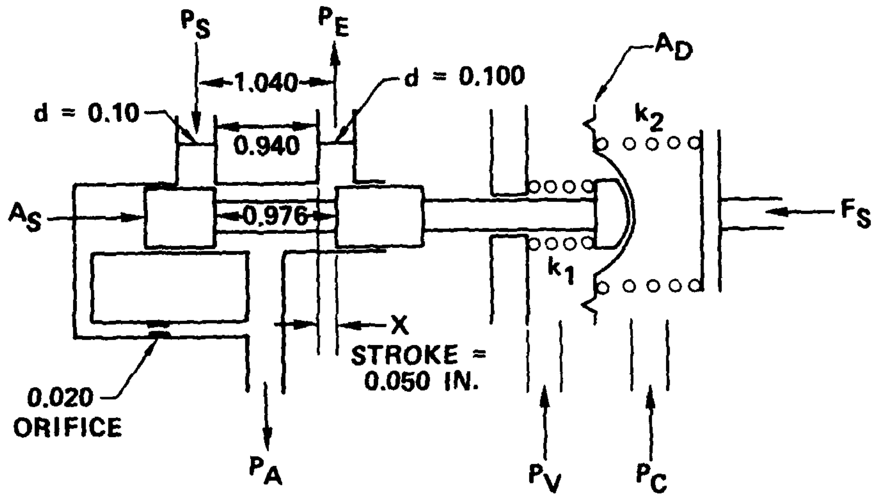


Figure D-1. Schematic of spool-type servovalve.

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